Accretion

Consider matter falling from infinity towards a object of mass M_* at a rate of $\dot{M}$. By the time that particle reaches radius R_*, it must release GM_*/R_* of potential energy, so the potential luminosity of this accretion is $L_{\text{acc}} = G\, M_*\, \dot{M} \,/\, R_*$.

Now consider accretion onto a black hole. Since the Schwartzschild radius of a black hole is $R_s = 2GM/c^2$, accretion onto it must release ~ $L_{\text{acc}} \sim \eta\, \dot{M}\, c^2$ of luminosity, where η is an efficiency factor. (If all the energy were radiated into space, η=0.5, but some may be lost in other ways, so η ~ 0.1 For comparison, in hydrogen fusion, η = 0.007.)

The moral: it is possible to get a lot of energy out of accretion. Since we see evidence for extraordinary amounts of energy coming from the nuclei of some galaxies, the assumption is that accretion is responsible.

Radiative Transport of Energy

Consider the outward diffusion of energy

- $U = a\,T^4$ the energy density region with temperature T
- l = the mean free path of the photons, i.e., $l = 1/\kappa\rho$

Since the photons are diffusing in 3 directions, 1/6 will be diffusing outward across a boundary in z. Meanwhile, 1/6 of the photons on the other side of the boundary will be diffusing the other way. In other words,

$$F_1 = \frac{1}{6} c\, U_{z-l} \quad \text{and} \quad F_2 = \frac{1}{6} c\, U_{z+l} \quad \text{so} \quad F_1 - F_2 = \frac{1}{6} c \left(U_{z-l} - U_{z+l} \right)$$

So the net flux across a radial boundary will be

$$F = -\frac{1}{3} c\, l \frac{dU}{dz} = -\frac{1}{3} c\, l \left(4aT^3 \frac{dT}{dz} \right) = -\frac{4acT^3}{3\kappa\rho} \frac{dT}{dz}$$

The Eddington Luminosity

Radiation can exert a pressure on matter, and, if the radiation is great enough, this pressure can overcome gravity. To see when this occurs, let's consider the equation for energy diffusion. If the diffusion is spherically symmetric, then

$$F = \frac{L}{4\pi R^2} = -\frac{4acT^3}{3\kappa\rho}\frac{dT}{dr} \quad \Rightarrow \quad L = -\frac{16\pi ac}{3\kappa\rho} R^2 T^3 \frac{dT}{dr}$$

Now if radiation is the dominant pressure term

$$P_{rad} = \frac{1}{3} a T^4 \quad \Rightarrow \quad \frac{dP}{dr} = \frac{4}{3} a T^3 \frac{dT}{dr}$$

and this can be substituted into the diffusion equation

$$L = -\left(\frac{16\pi a c R^2 T^3}{3\kappa\rho}\right)\left(\frac{3}{4aT^3}\right)\frac{dP}{dr} = -\frac{4\pi c}{\kappa\rho} R^2 \frac{dP}{dr}$$

For high temperatures and low densities, electron scattering is the main source of opacity, so $\kappa = n_e \sigma_e / \rho = \sigma_e / m_{\rm H} = 0.2\ (1 + X)$, where X is the hydrogen fraction (generally 0.75).

The Eddington Luminosity

Finally, consider the case where the outward pressure from radiation is exactly balanced by gravity. In that case, hydrostatic equilibrium must hold, i.e.,

$$\frac{dP}{dr} = -\frac{GM}{R^2}\rho$$

so

$$L = -\frac{4\pi c}{\kappa\rho} R^2 \frac{dP}{dr} \quad \Rightarrow \quad L_E = \frac{4\pi c G M}{\kappa} = 1.4 \times 10^{38} \left(\frac{M}{M_\odot}\right) \text{ ergs/s}$$

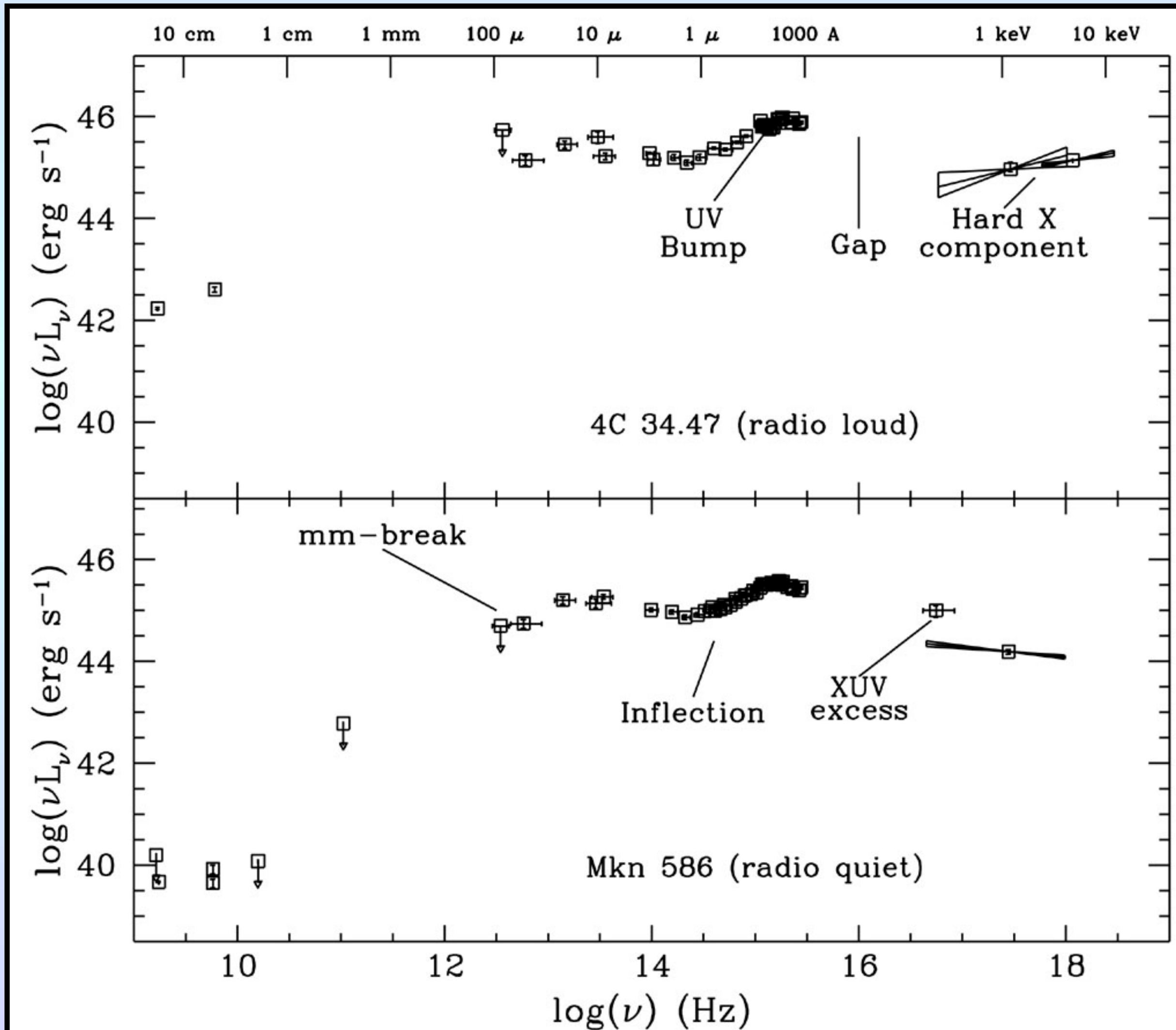
This is the Eddington luminosity. For an object to be stable, the luminosity of that object must be less than L_E. If we compare this to the luminosity generated by accretion, then

$$L < L_E \quad \Rightarrow \quad M_E < \frac{L \sigma_e}{4\pi c G m_H} \quad \text{and} \quad \dot{M} < \frac{L_E}{\eta c^2}$$

General Properties of AGN

Active Galactic Nuclei come in many flavors, but there are some properties than underlie the entire phenomenon:

• Most AGN can be observed from the hard X-ray to the millimeter (and some even in the radio).



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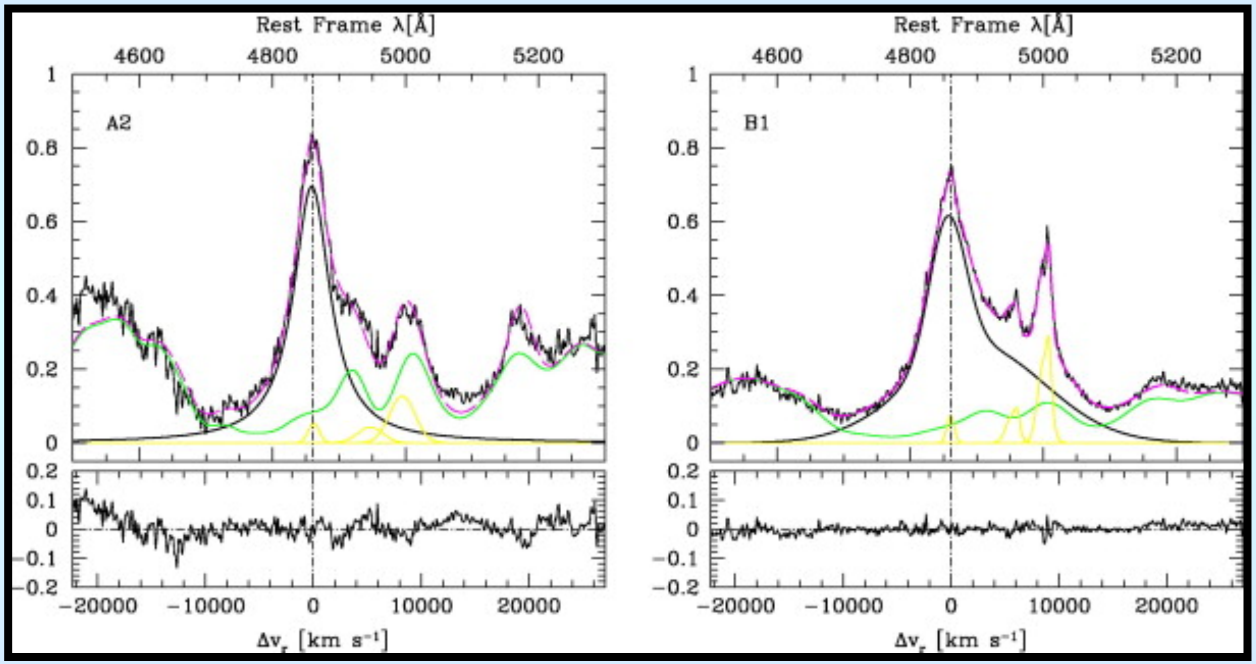
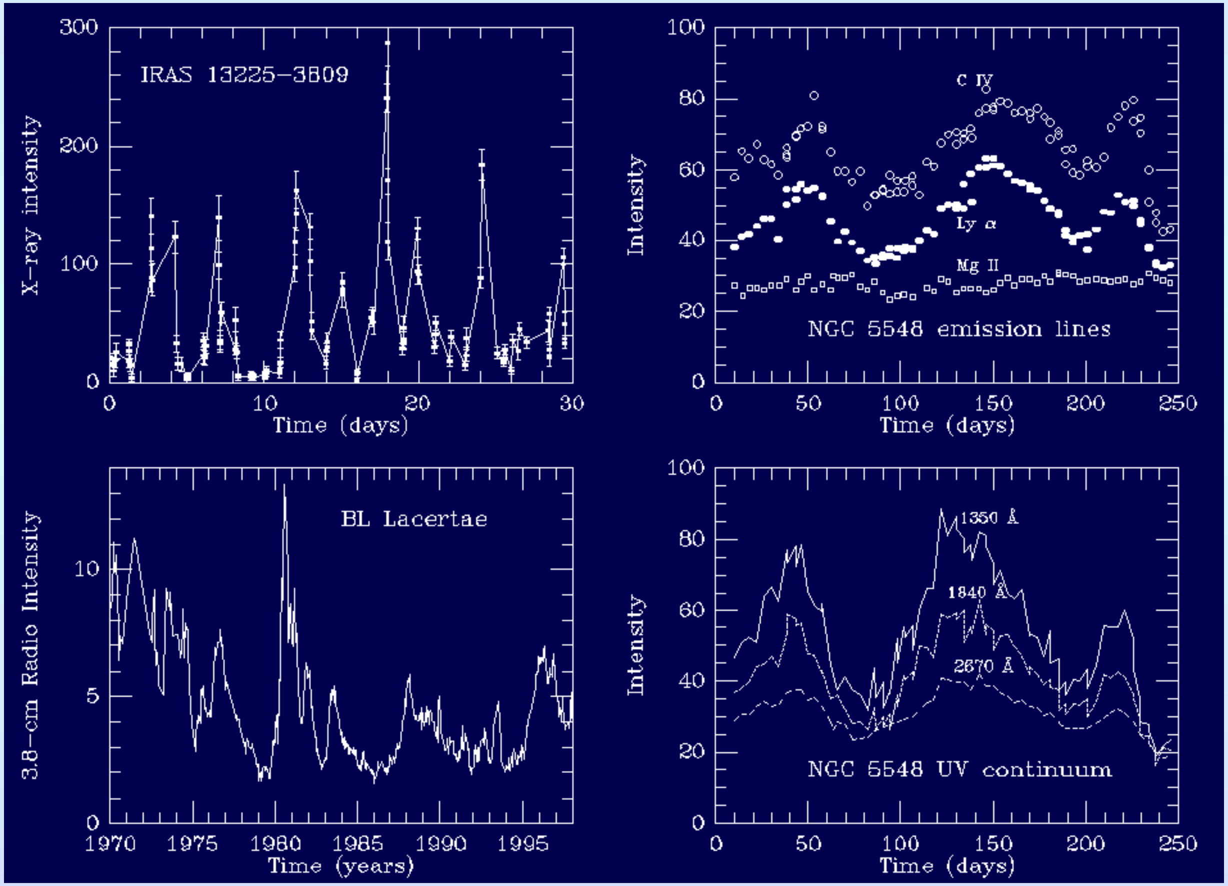


General Properties of AGN

Active Galactic Nuclei come in many flavors, but there are some properties than underlie the entire phenomenon:

- Most AGN can be observed, from the hard x-ray to the millimeter (and some even in the radio).
- Broad forbidden emission lines and very broad permitted emission lines.
- Variability of time-scales of days/weeks/ or months



Classes of **A**ctive **G**alactic **N**uclei

Depending on what we see, AGN can broadly be classified into several catagories:

- **Seyfert galaxies**: spiral galaxies with bright nuclei containing broad (> 5000 km/s) permitted emission lines (i.e., H, He, CNO, and Fe) and "narrow" (~ 500 km/s) forbidden lines (O, N, Ne, etc.). Usually sub-classed as Seyfert 1 (strong broad lines) and Seyfert 2 (no broad lines). Non-integer sub-classes are allowed. Usually bright in X-rays.

- **Radio galaxies**: elliptical galaxies with nuclear emission (similar to Seyferts) and bright ($L > 10^{42}$ ergs/s) non-thermal radio jets that can extend up to 10 Mpc! Usually sub-classed as Broad-Line and Narrow-Line Radio Galaxies (in analogy to Seyfert galaxies), and as Fanaroff-Riley Type I and Type II, depending on the morphology of the radio emission.

Classes of **A**ctive **G**alactic **N**uclei

Depending on what we see, AGN can broadly be classified into several catagories:

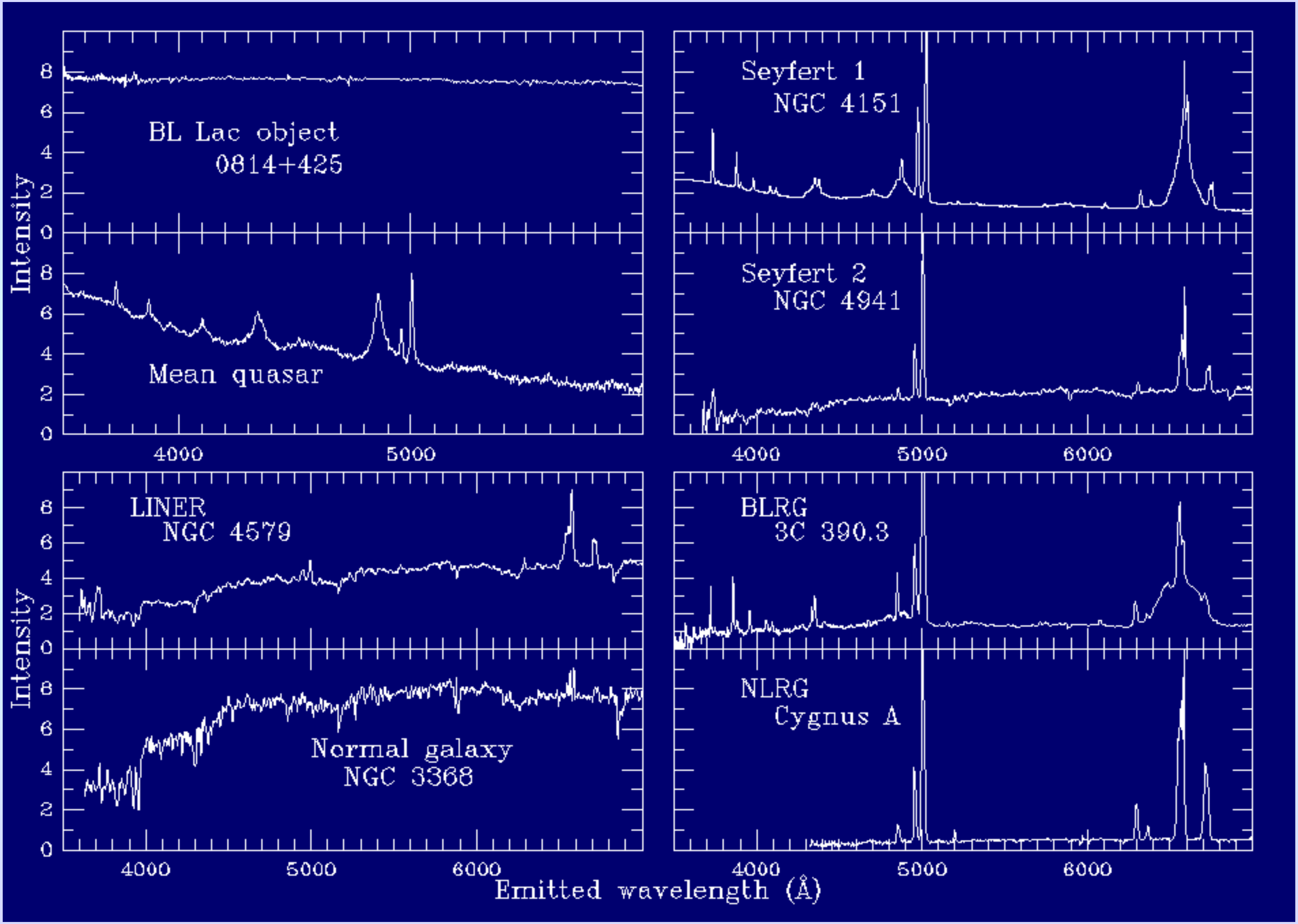
- **LINERS**: galaxies with **L**ow-**I**onization **N**uclear **E**mission **R**egions. Galaxies (typically nearby) with nuclear emission lines from species such as [O I]. Perhaps half of all nearby spirals are LINERS (to some degree). There is much debate whether all LINERS are caused by AGN.

- **Blazars**: Radio-bright point-source objects with featureless spectra, high polarization, and variability on time scales of days. Also known as Optically Violent Variables (OVVs) and BL Lac objects.

Classes of **A**ctive **G**alactic **N**uclei

Depending on what we see, AGN can broadly be classified into several catagories:

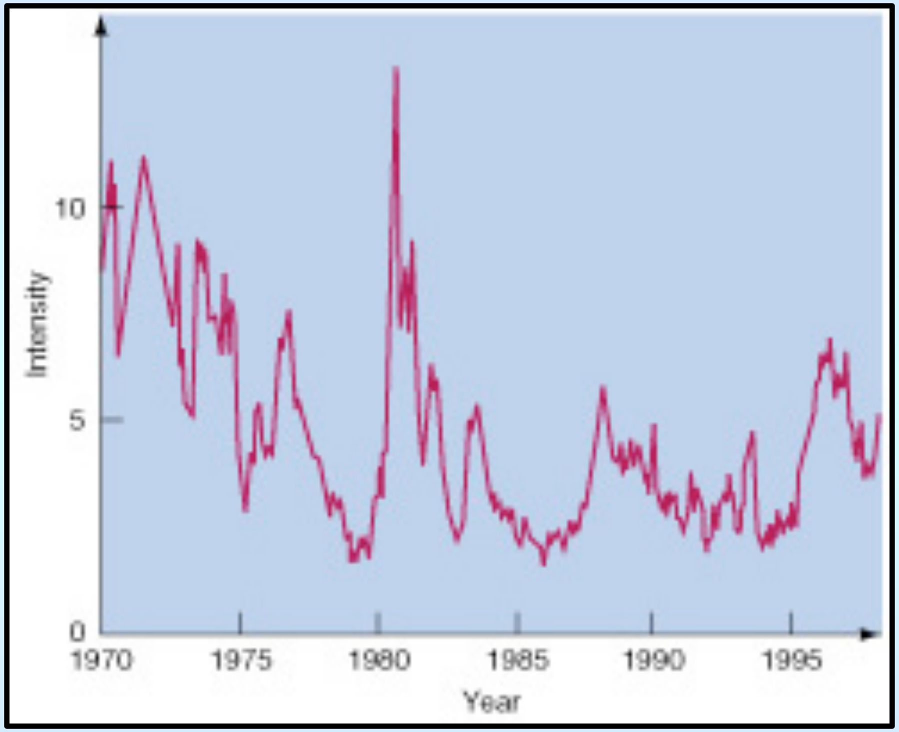
- **Quasars**: Extremely luminous ($L > 10^{13}\ L_\odot$) unresolved objects with broad (~ 10,000 km/s) permitted emission-lines and "narrow" (~ 500 km/s) forbidden lines. Although originally discovered in the radio (hence the acronym Quasi Stellar Radio Source), most are radio-quiet. Virtually all are bright in X-rays.

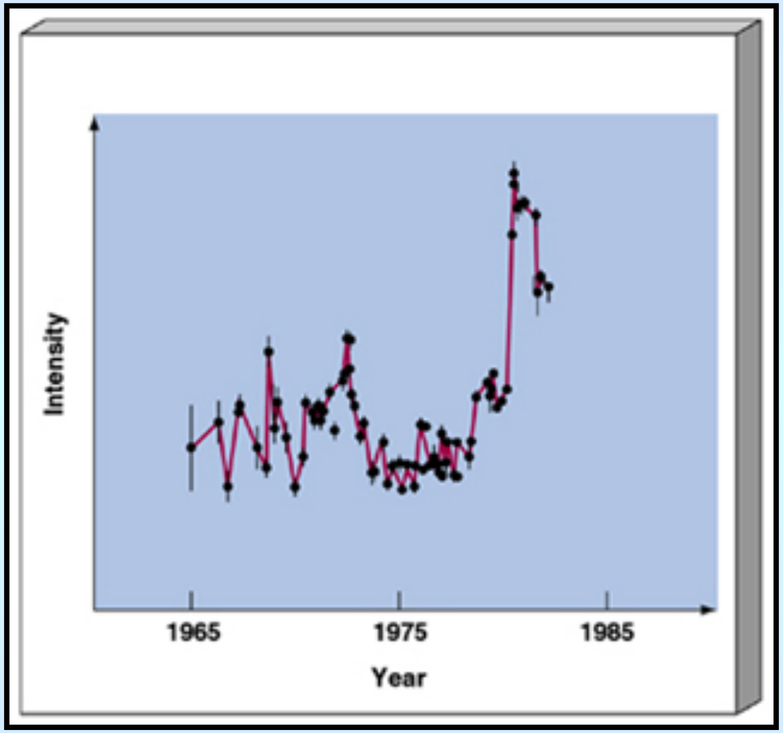


BL Lac object
0814+425
Mean quasar
Seyfert 1
NGC 4151
Seyfert 2
NGC 4941
LINER
NGC 4579
Normal galaxy
NGC 3368
BLRG
3C 390.3
NLRG
Cygnus A
Intensity
Emitted wavelength (Å)
0
2
4
6
8
4000
5000
6000

Size and Variability

Since many AGN vary in brightness we have a crude way to estimate their size.

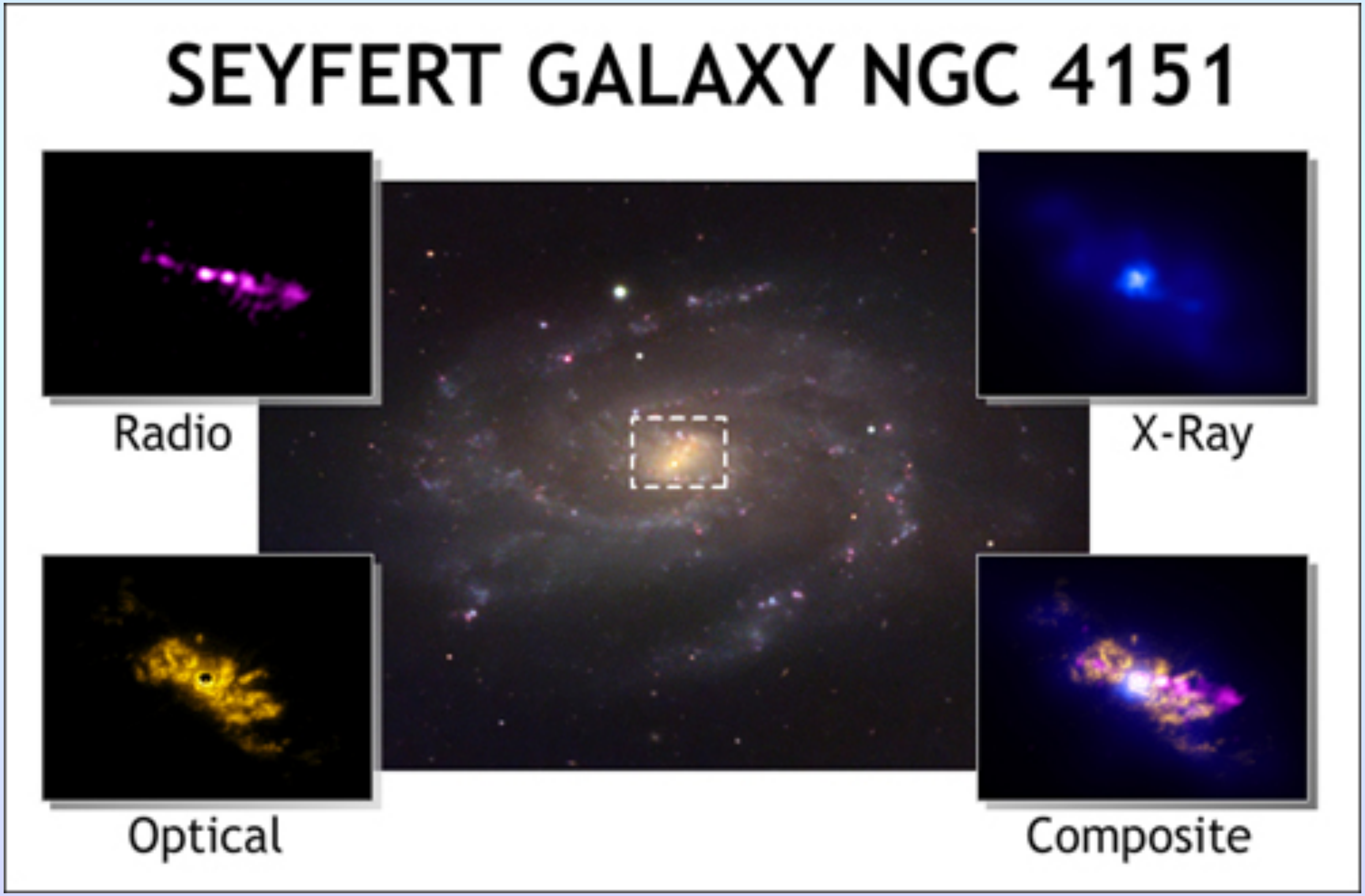




Whatever mechanism it is that causes an AGN to brighten sends a signal out no faster than the speed of light, Thus, if it takes a few weeks or months to brighten, then the object must be no bigger than a few light-weeks/months across.

X-ray Emission

Most AGN emit over a very broad wavelength range from the IR to the X-ray. But since few objects are hotter than ~ 10^6 K, X-rays are perhaps the best way to identify AGN.



X-ray Identifications

Because accretion disks around compact objects can get much hotter than stars, X-ray surveys can identify them.

Digital Sky Survey

ROSAT All Sky Survey

Almost all X-ray sourses are either compact accreting objects, chromospherically active stars, or galaxy clusters.

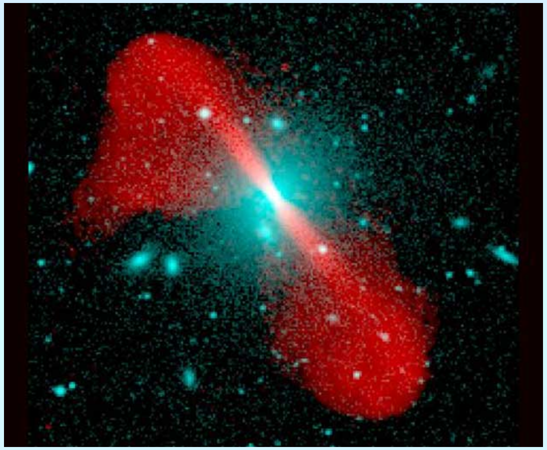
Explaining X-ray Emission

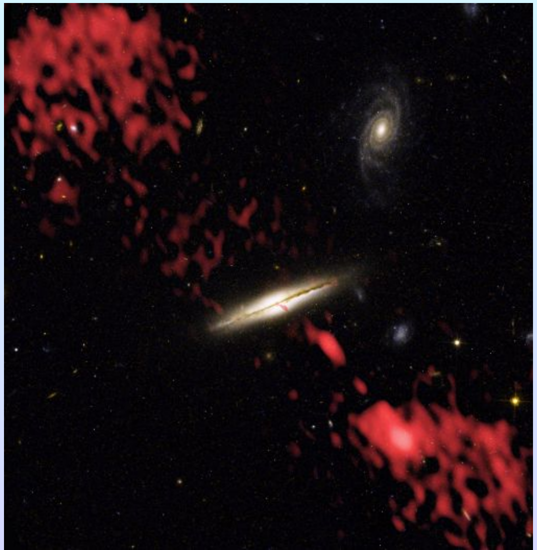
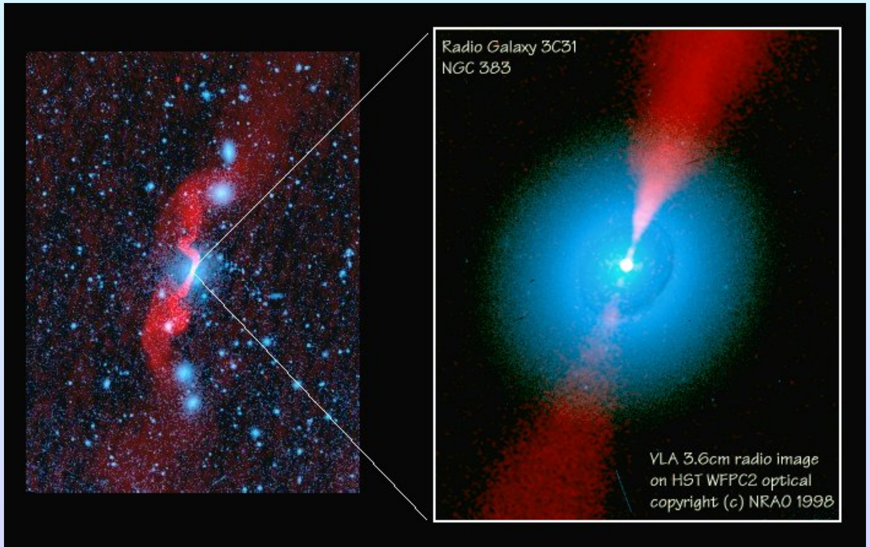
The X-ray emission is likely coming from the inner parts of an accretion disk. Near a black hole, the Keplerian rotation velocity approaches the speed of light. Viscosity (friction) in the disk a few Schwartzschild radii from the black hole can produce X-rays.

The temperature of the disk depends on the speed of the gas. Near the event horizon, the viscosity produces X-rays. At larger radii, where the gas revolves more slowly, optical and infrared light is emitted.

Synchrotron Jets

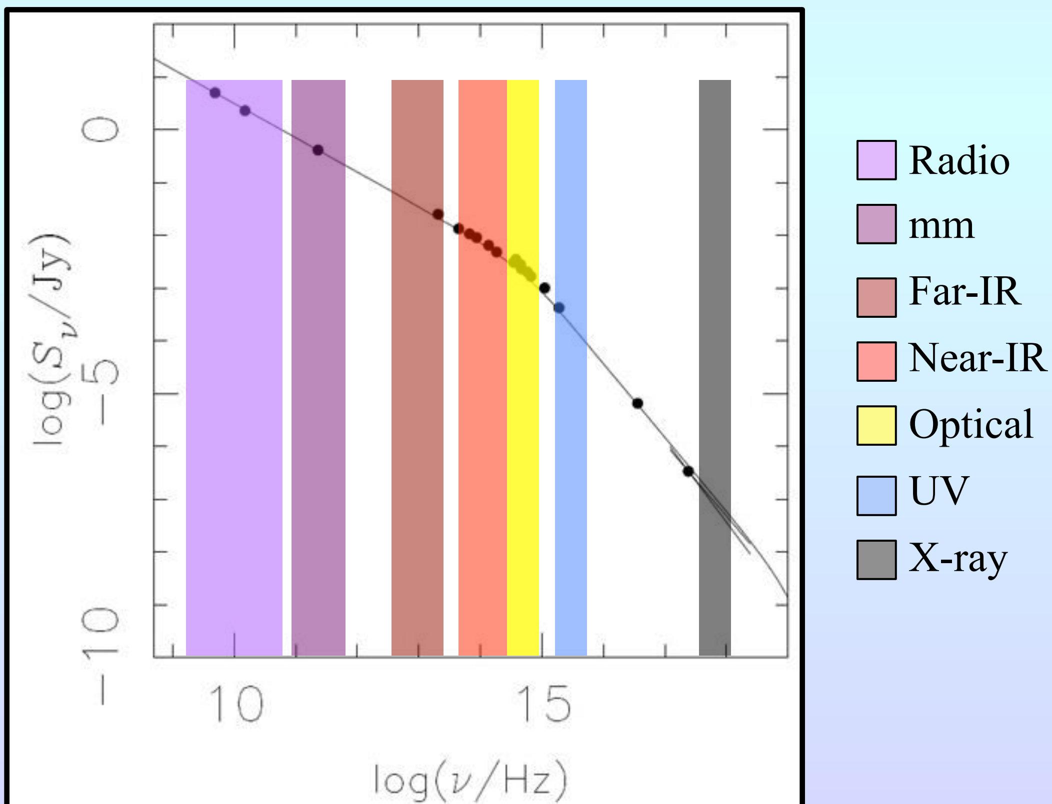
Many AGN emit jets of relativistic electrons (and ions) out their poles. These particles may quickly collide with the surrounding interstellar medium, but if they don't they will spiral around magnetic field lines are create synchrotron radiation.

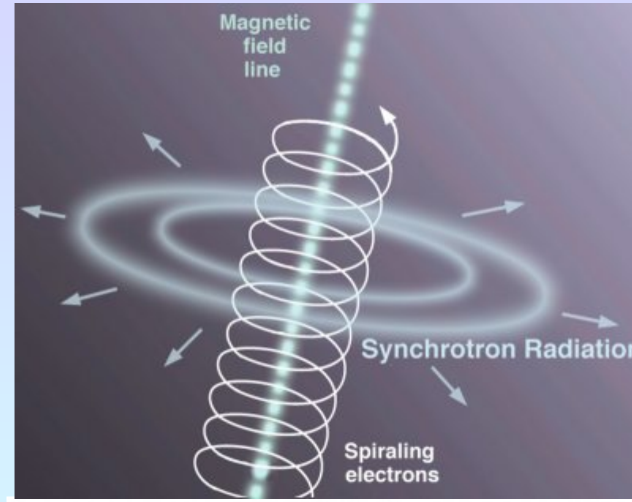



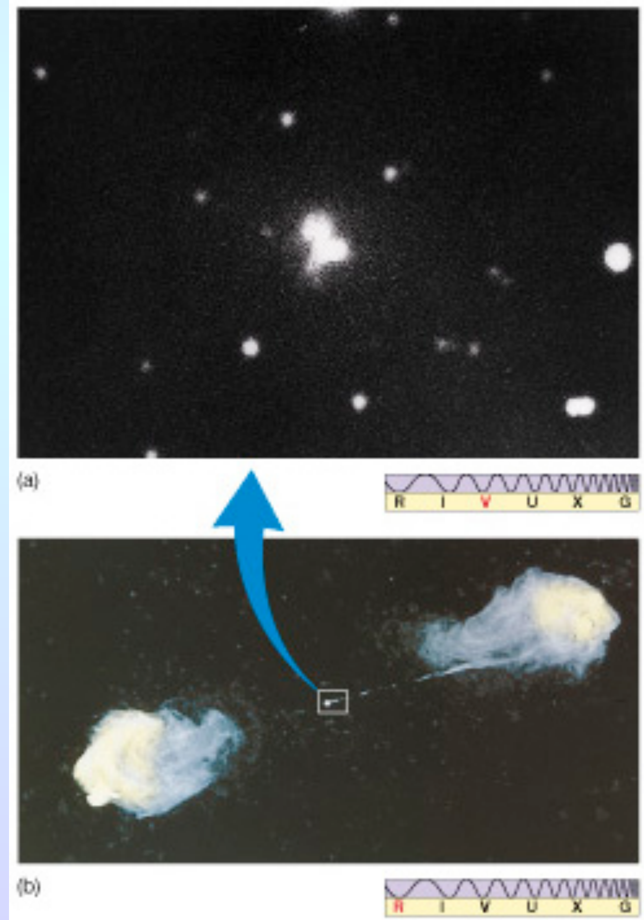



Explaining Radio Emission

Synchrotron radiation takes the form of a power law that extends from the radio to some high-energy cutoff. Most times this cutoff is somewhere in the IR, but some are present in the optical and at higher energies.



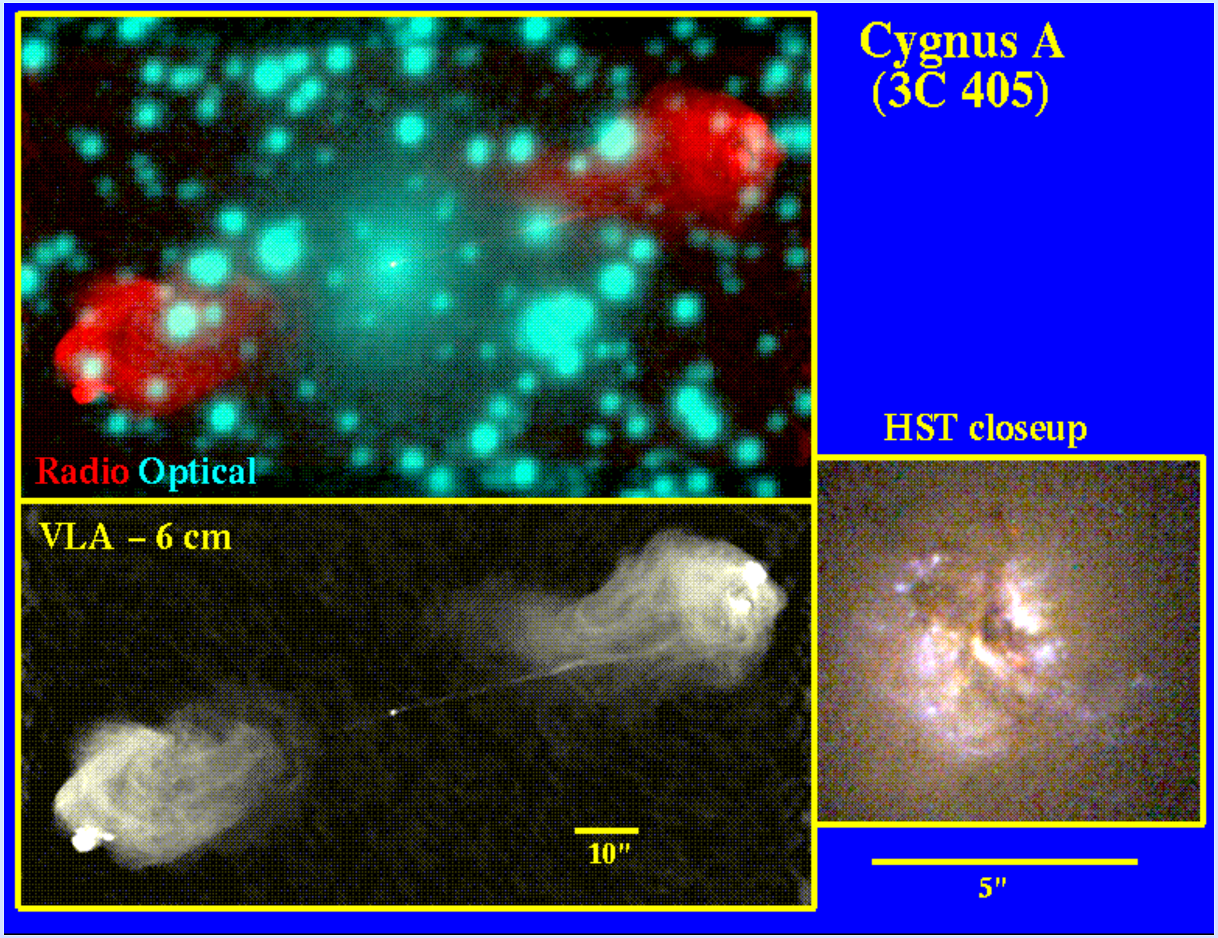




Jet Orientations

Since the electrons are relativistic, the orientation of the jet can determine its properties.

If the orientation is across our line-of-sight, the result can be the double-lobed jet of Cygnus A.



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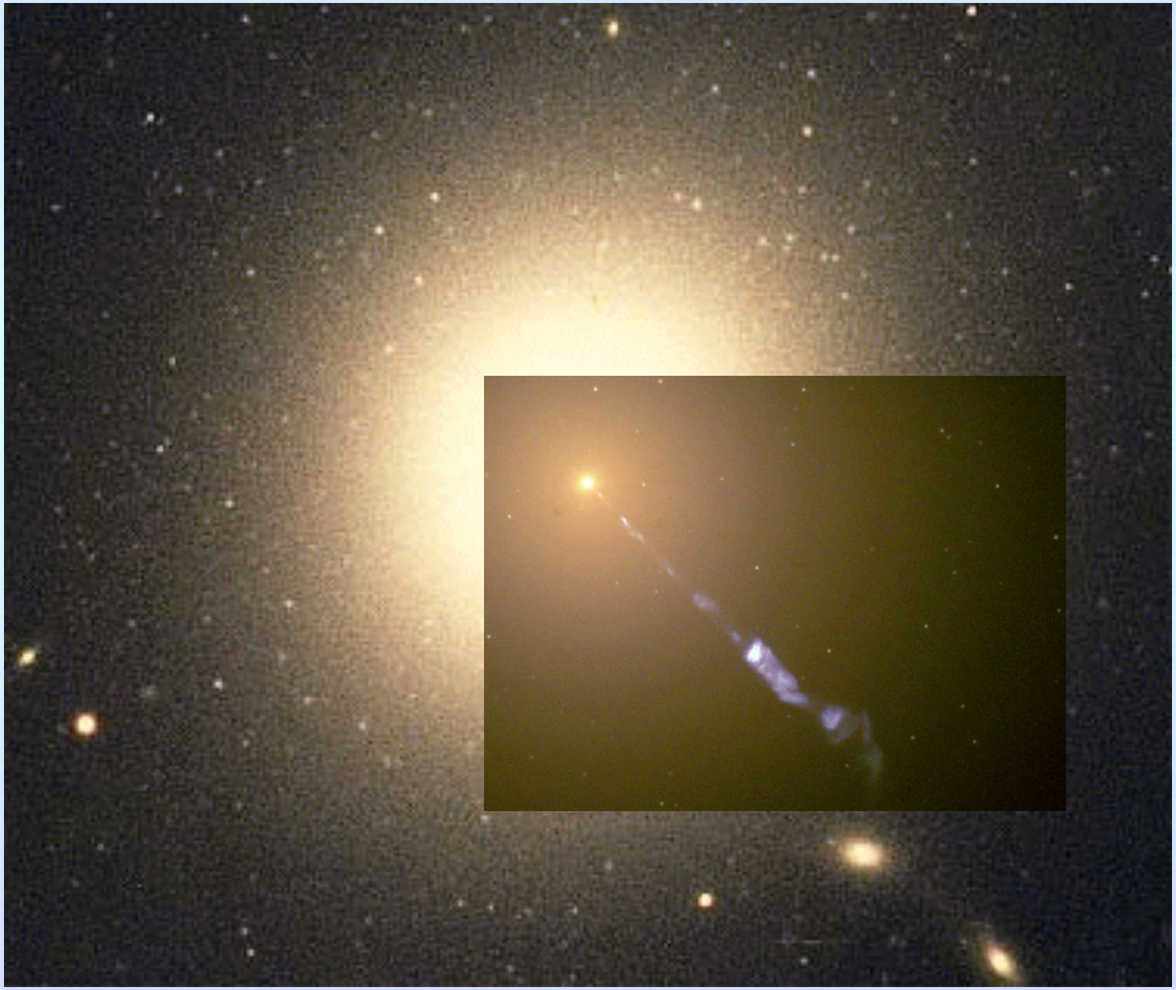

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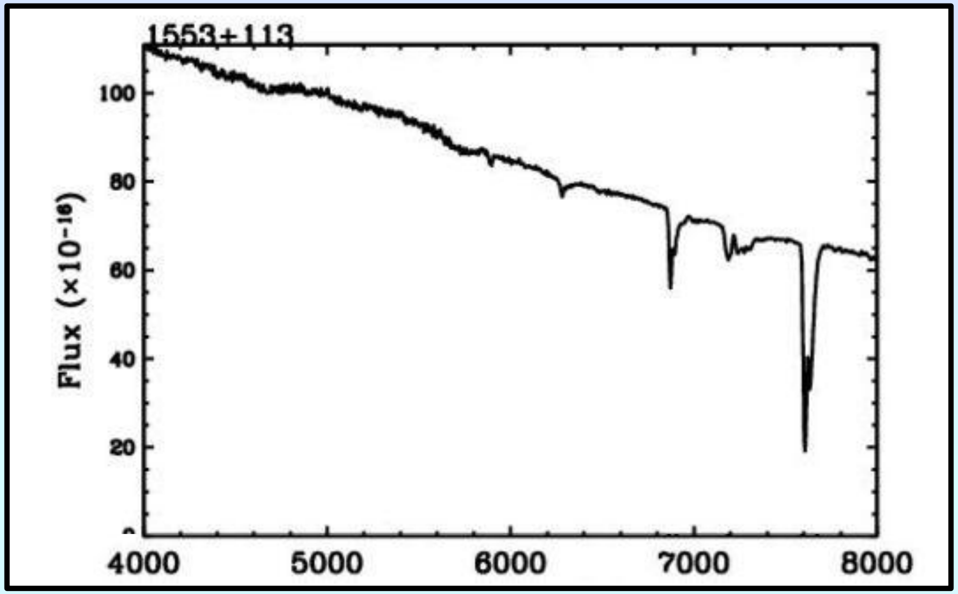

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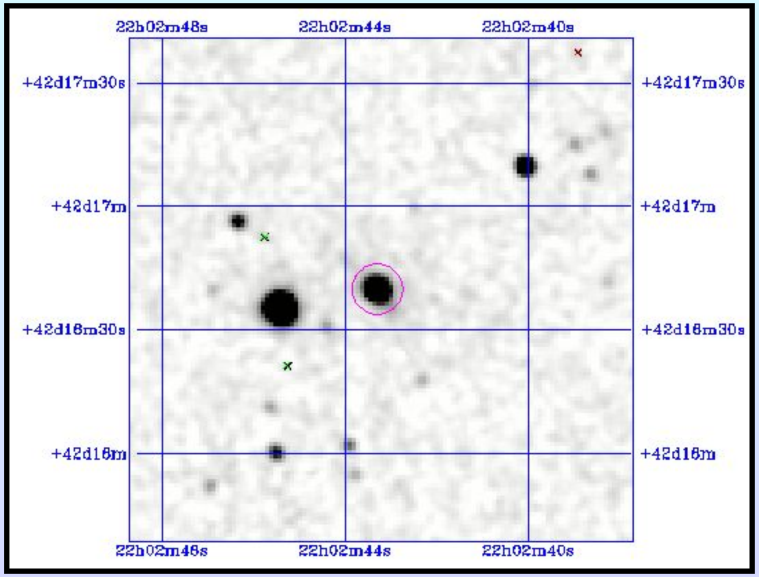
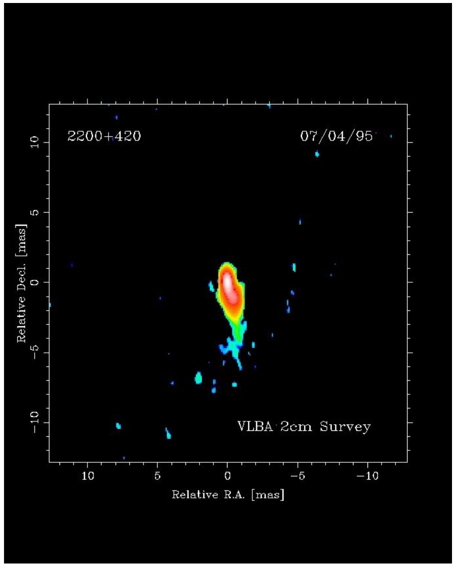
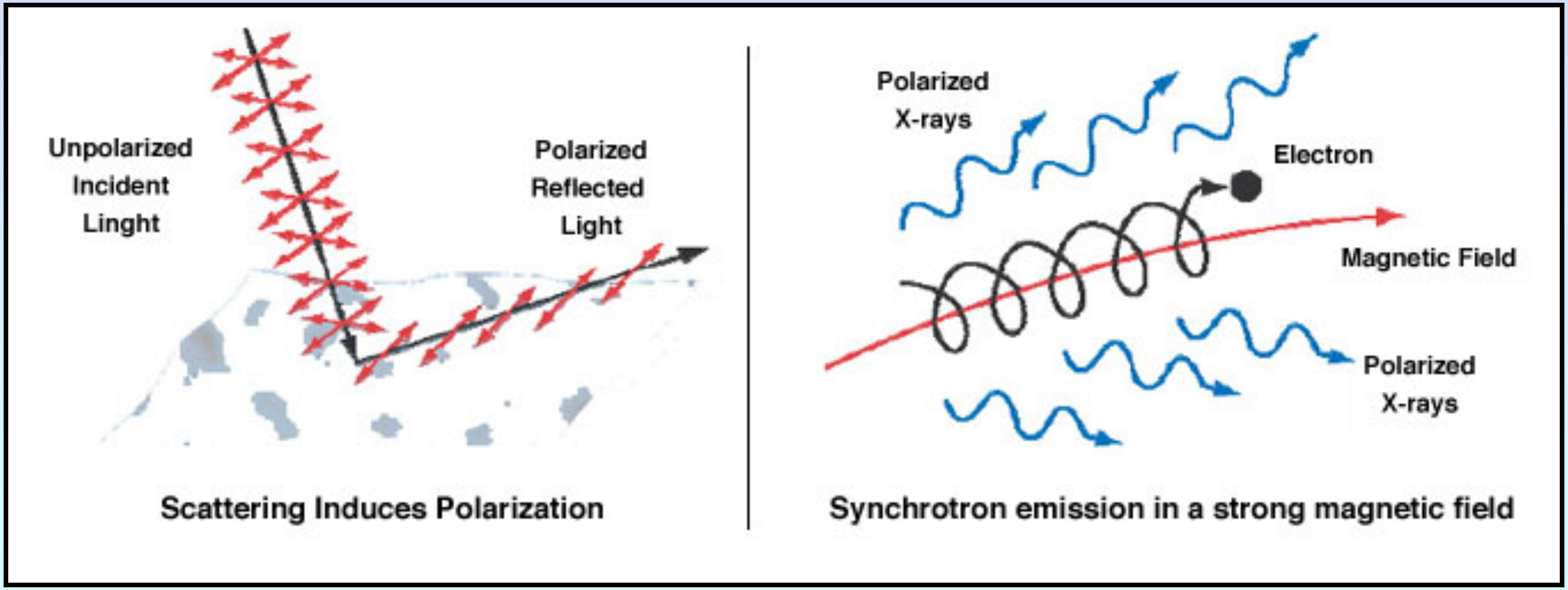
Finally, if jet is pointed directly at us, the result may be Blazar.

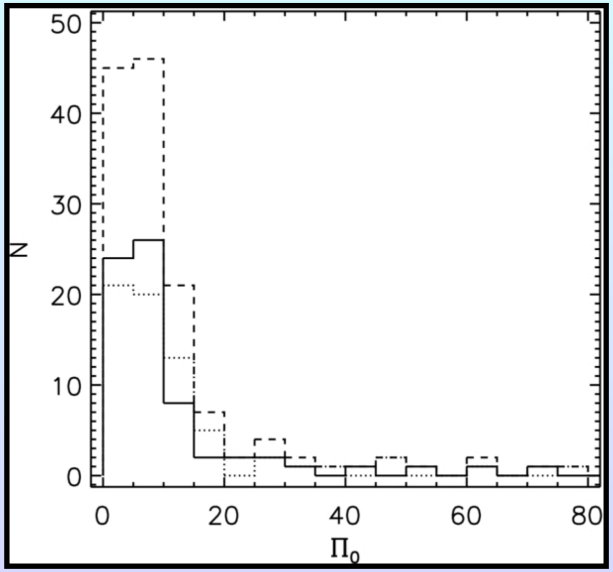




Polarization



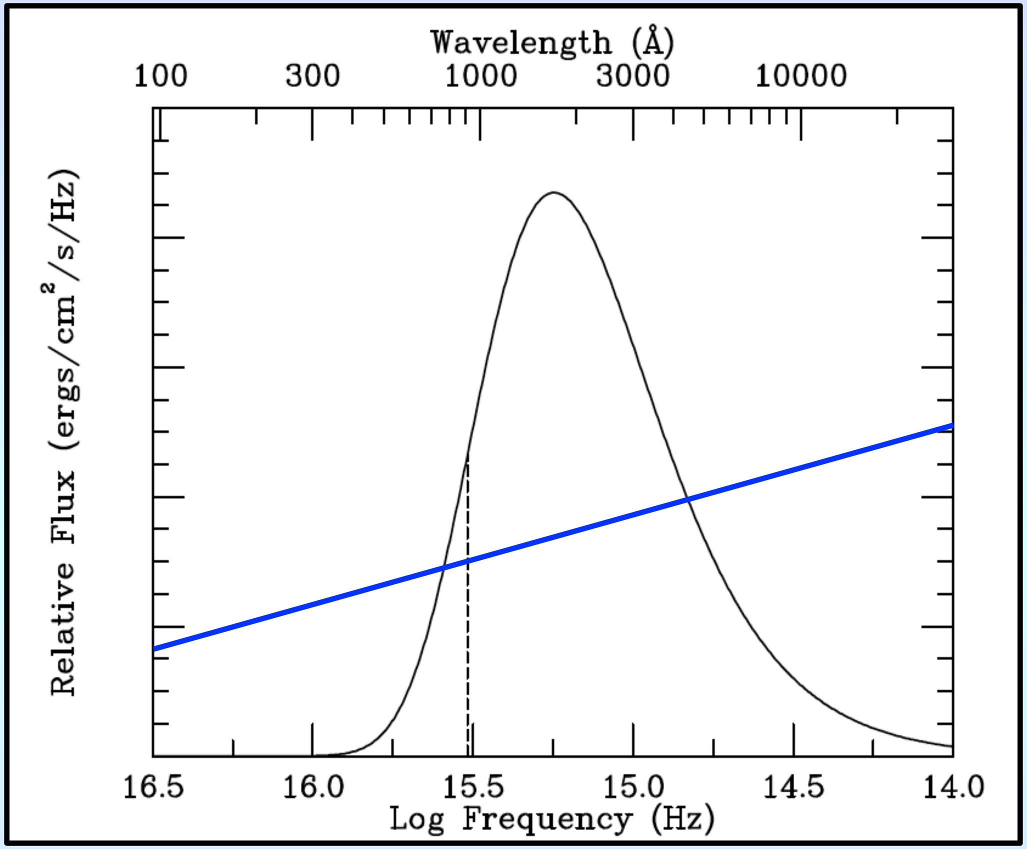
There are two common sources of polarization: scattering off dust grains and synchrotron radiation. Emission from jets and can be highly polarized, especially when the jet is pointed directly at you.



Explaining LINERS

Recall that the ionization cross-section is large at 13.6 eV, but then declines, with $a_\nu \propto \nu^{-3}$.

Also recall that at the border of the ionized region, an ionizing photon's mean free path is $(0.5\, N(\mathrm{H})\, a_\nu)^{-1}$. If the source of photons is "soft", then a_ν is large, the transition zone is thin, and free electrons are restricted to the ionized region.



However, if the source is hard, a_ν is small, the transition zone is large, and ionized electrons will collisionally excite material in low ionization states.

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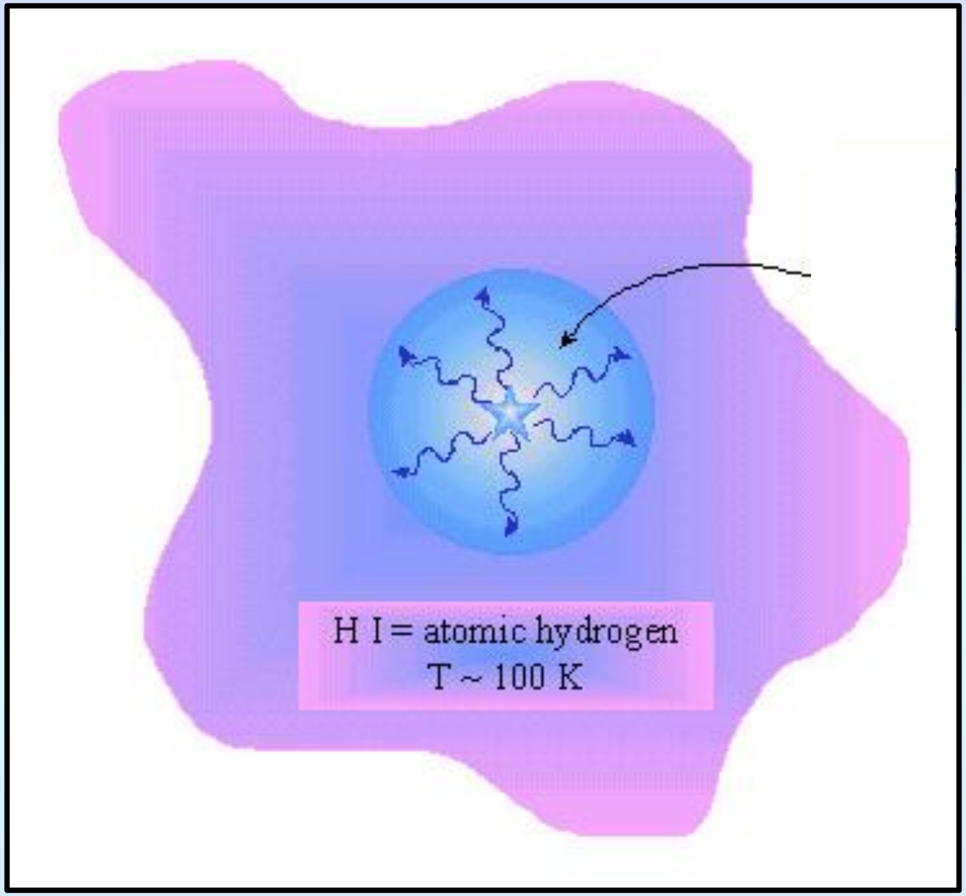

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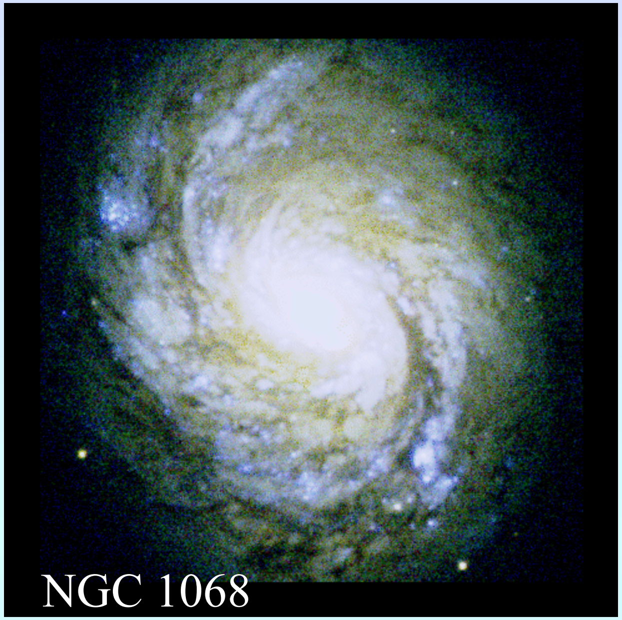
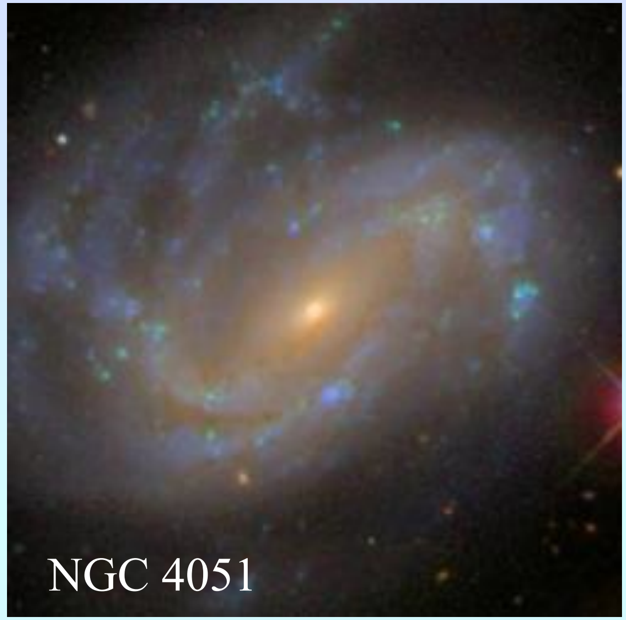
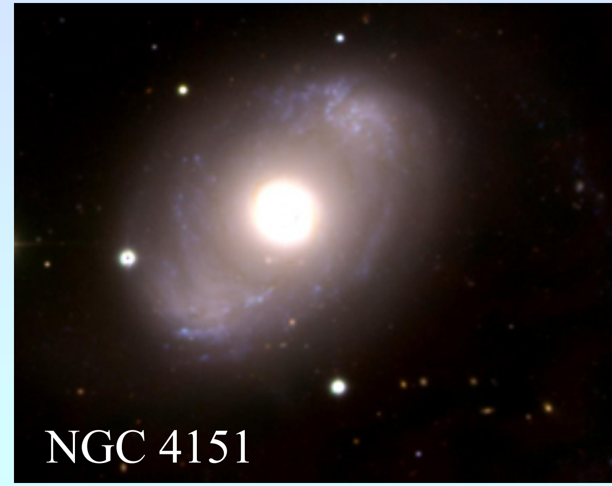
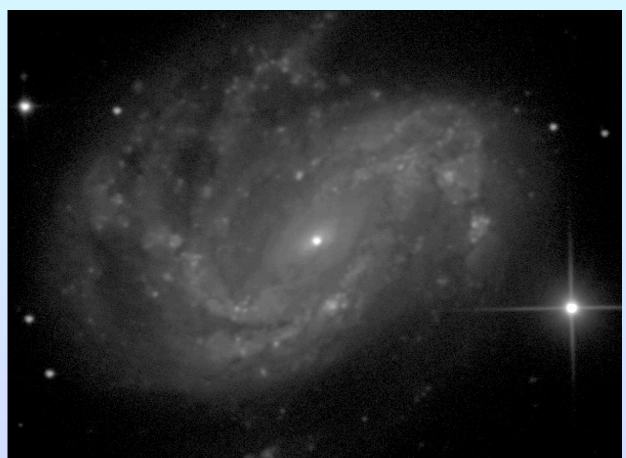
Seyfert Galaxies: The Prototypes

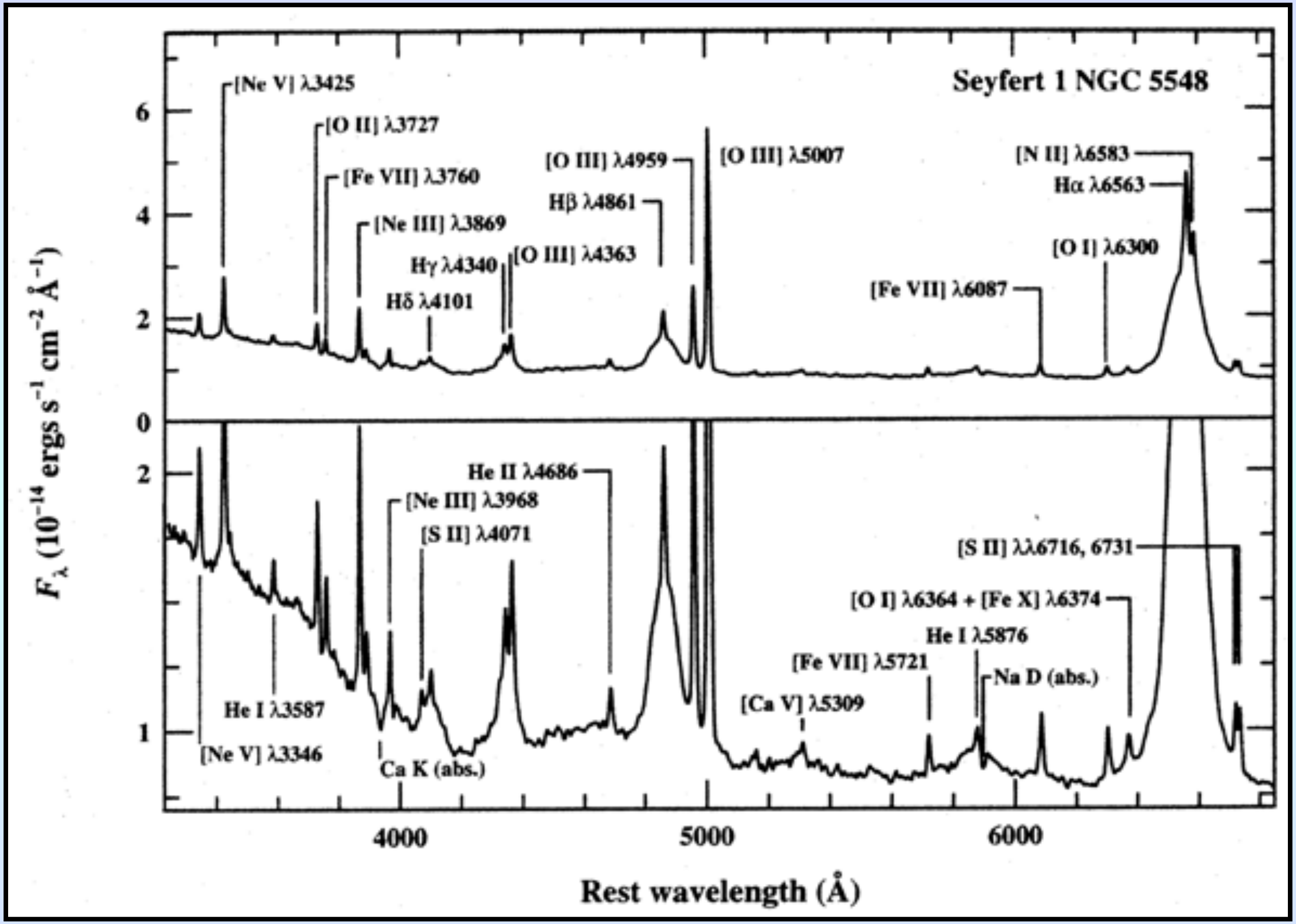






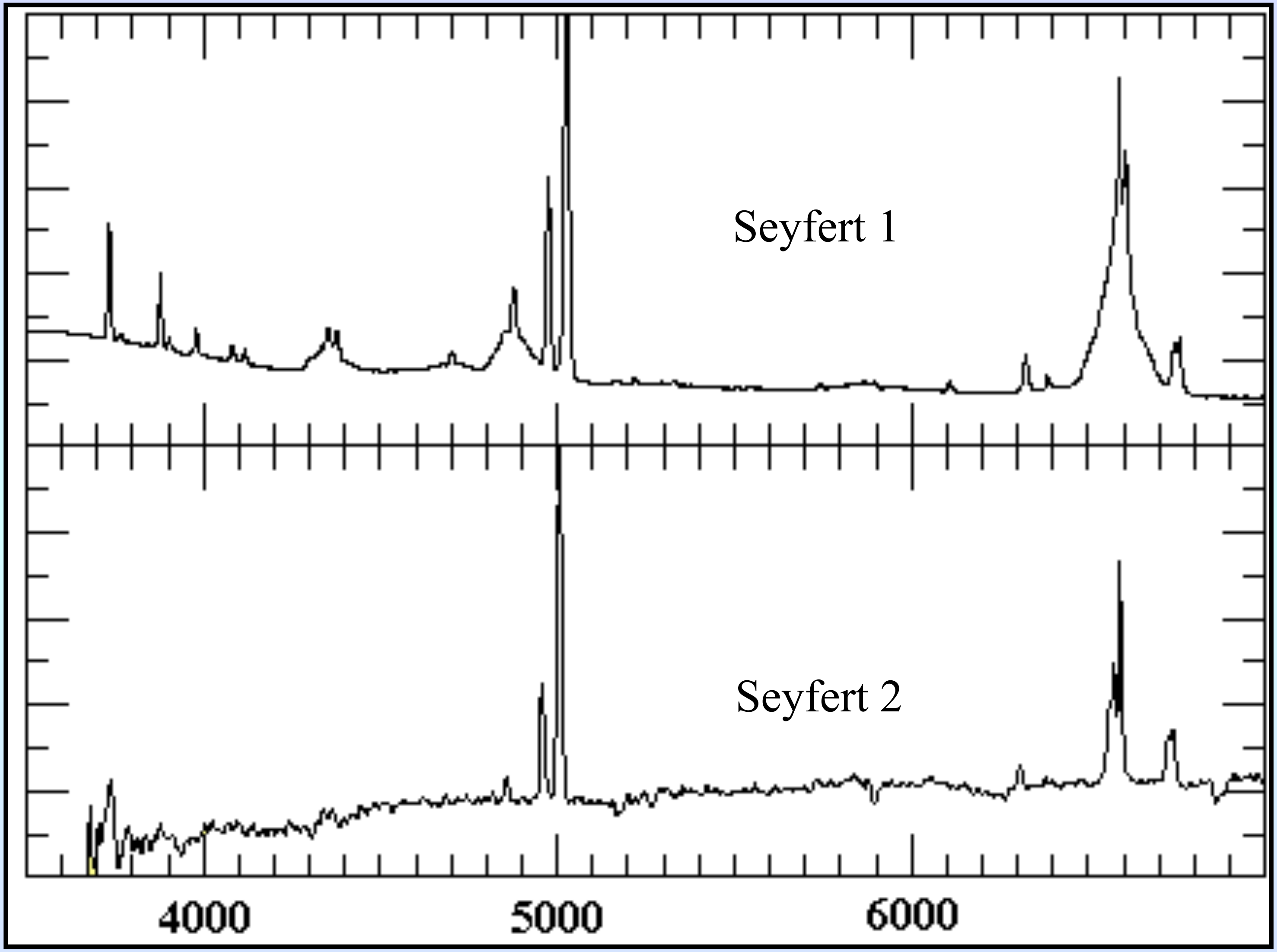


Seyfert 1 Spectrum



Seyfert 1 galaxies have very broad (~ 5,000 km/s) permitted lines (principally of H, He, and C), along with narrower forbidden lines.

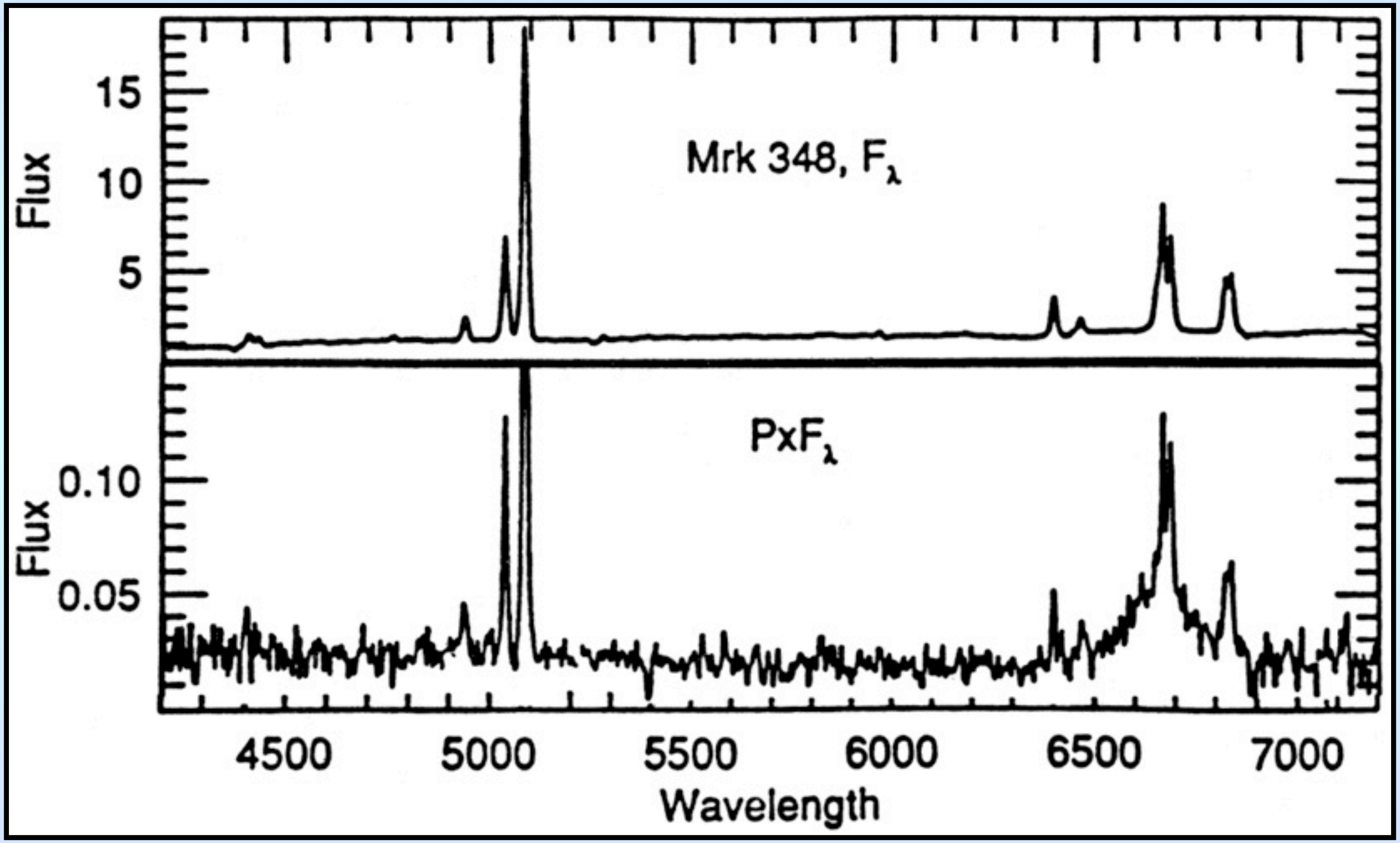
Seyfert 2 Spectrum



Seyfert 2's lack the broad emission features, but their narrow forbidden lines are much wider than those of normal galaxies.

Seyfert 2's in Polarized Light

When viewed in polarized light, Seyfert 2 galaxies show broad permitted lines, like Seyfert 1s.



This suggests that Seyfert 2 galaxies are actually Seyfert 1s, with their permitted lines obscured.

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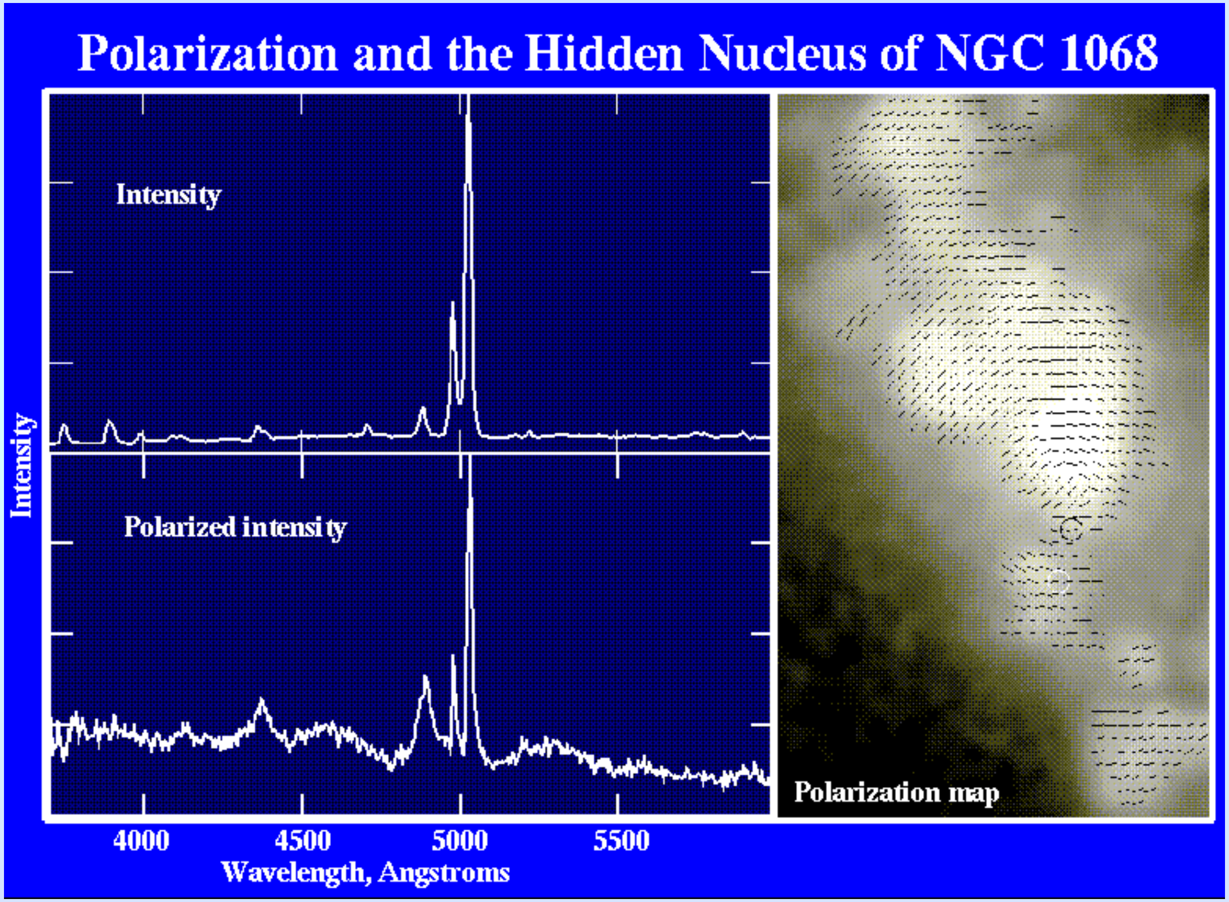

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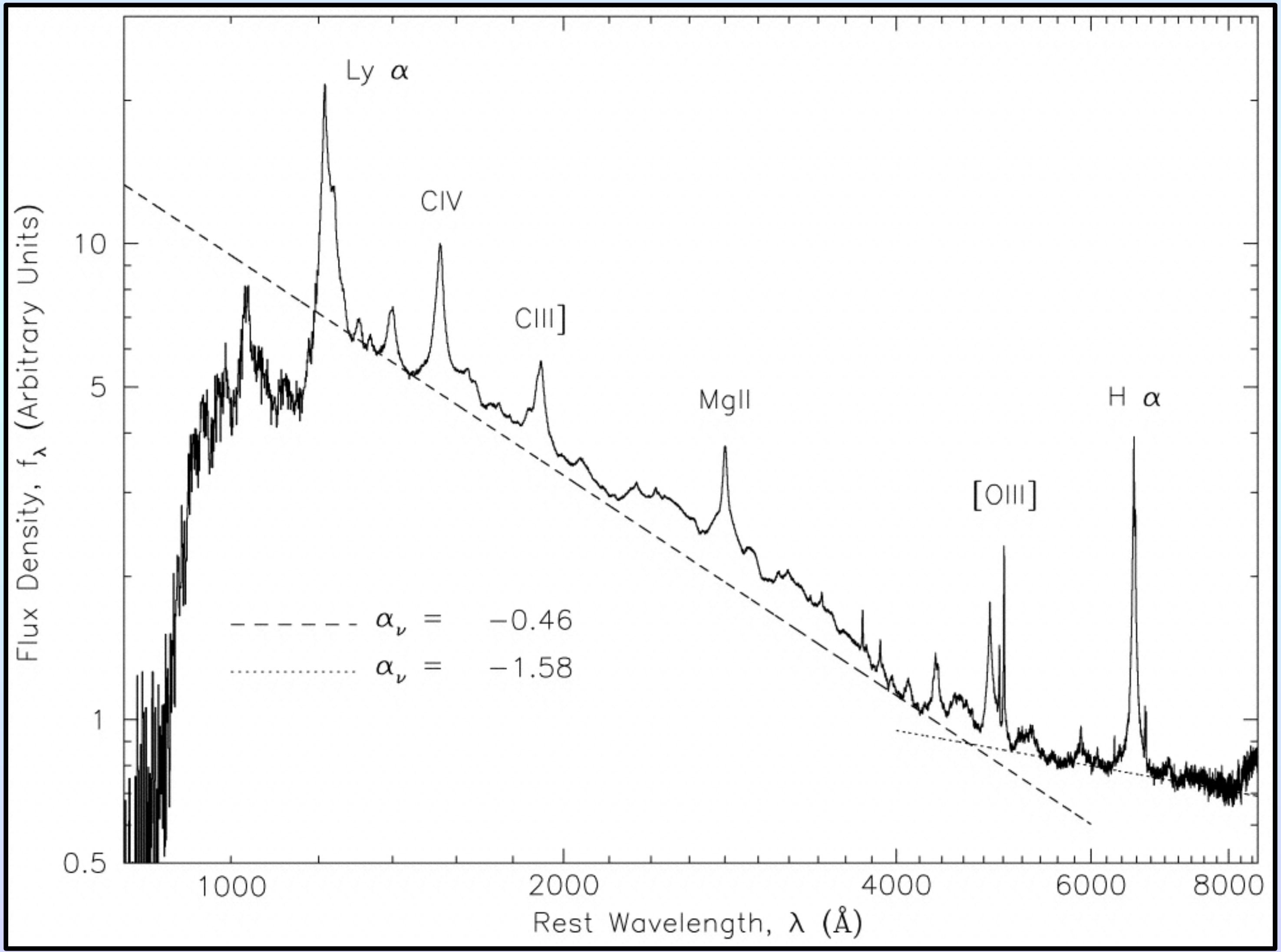
Source of Emission Lines

Most of what we know about the physical conditions around quasars come from their emission lines.

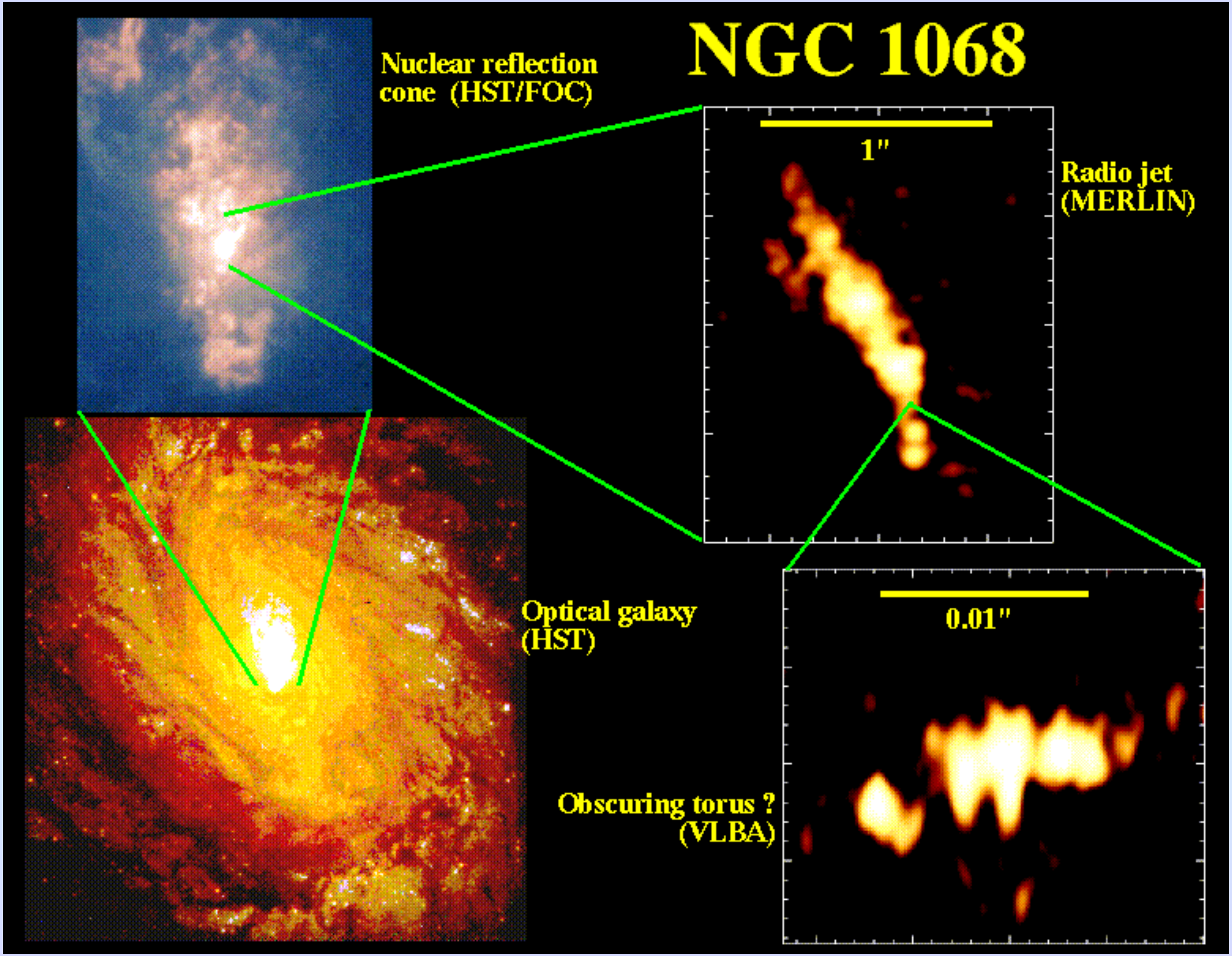


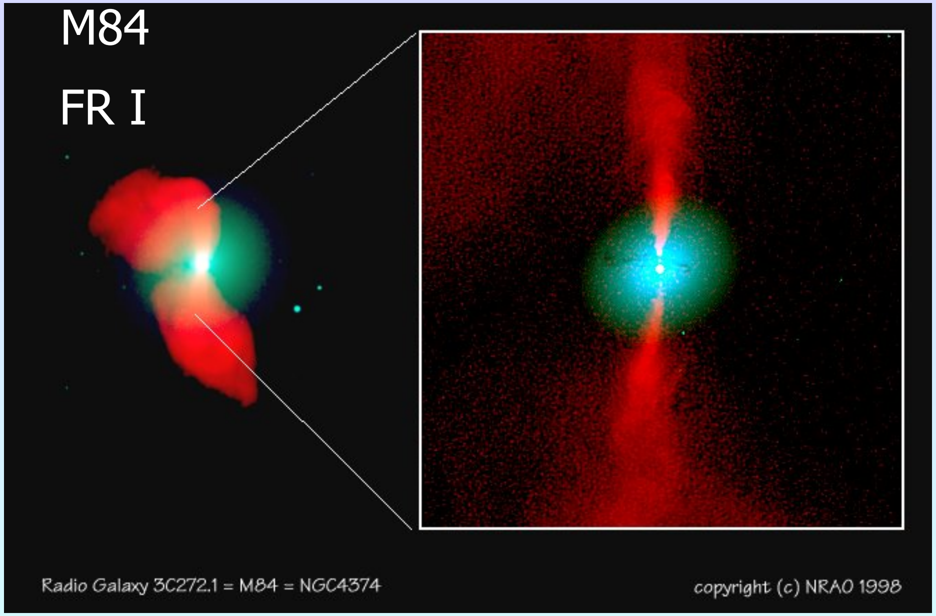
Source of Emission Lines

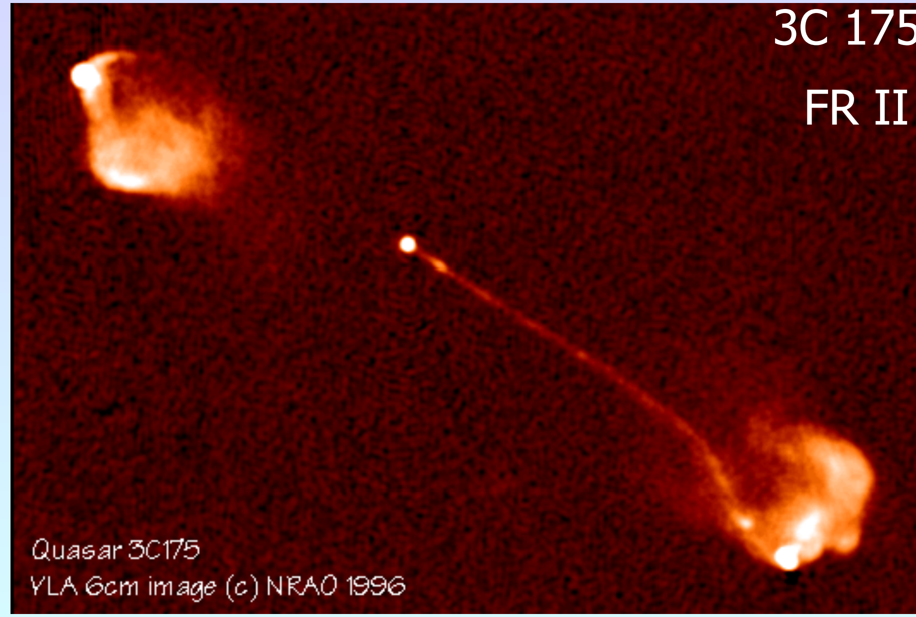
The critical density for most forbidden lines is $n_e \sim 10^6$ cm^{-3}; at higher densities, collisions de-populate the levels before spontaneous decay can occur. Since broad lines regions do not have forbidden lines, the local density must be $> 10^6$ cm^{-3}. (But C III] λ1909 is often seen, and this line has a critical density of ~ 10^{10} cm^{-3}.)

Based on the Balmer-line fluxes, and this density estimate, the broad-line region contains ~ 40 $M_\odot$, and is ~ 0.02 pc in size.

Using the same method (with better density constraints from the forbidden lines), the narrow-line region contains ~ 10^5 $M_\odot$ and has a radius of ~ 30 pc.


NGC 1068
Nuclear reflection cone (HST/FOC)
1"
Radio jet (MERLIN)
Optical galaxy (HST)
0.01"
Obscuring torus ? (VLBA)



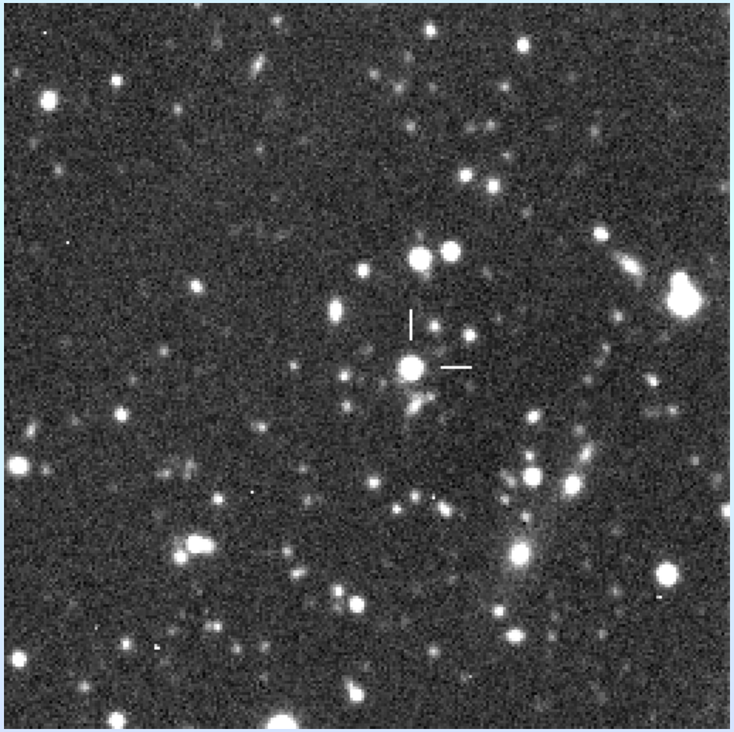


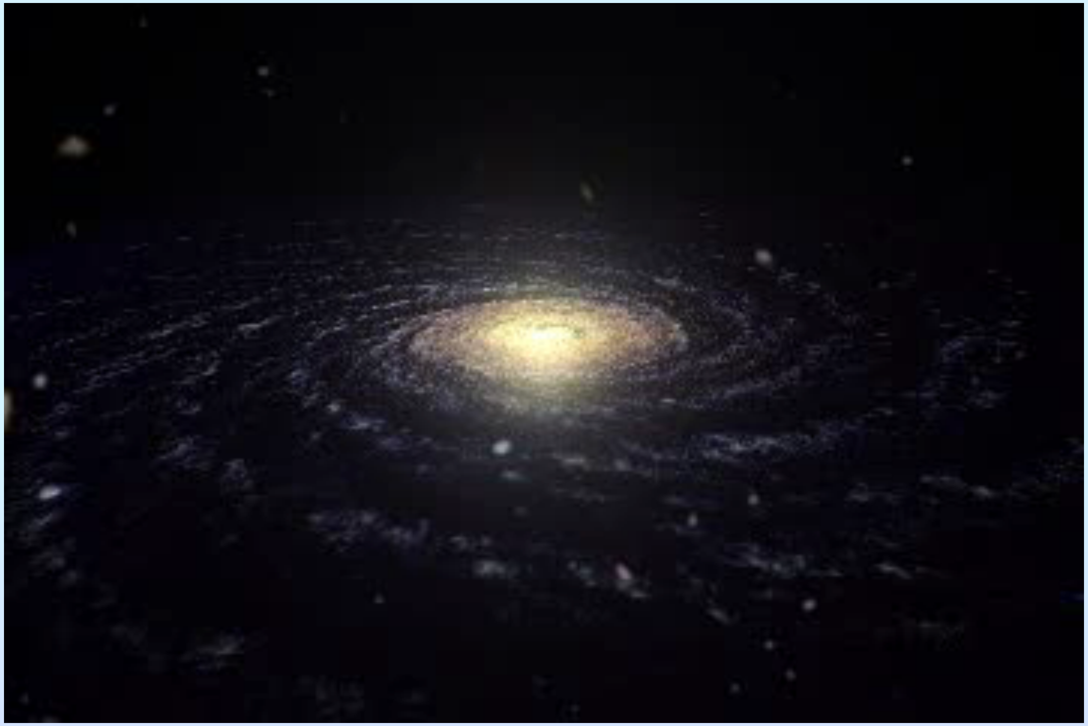
FR I: edge darkened radio jets, slower jet speeds, lower radio power, two sided jets

FRII: edge brightened radio jets, fast jet speeds ~ 0.1c, higher radio power, one sided jet or different luminosities

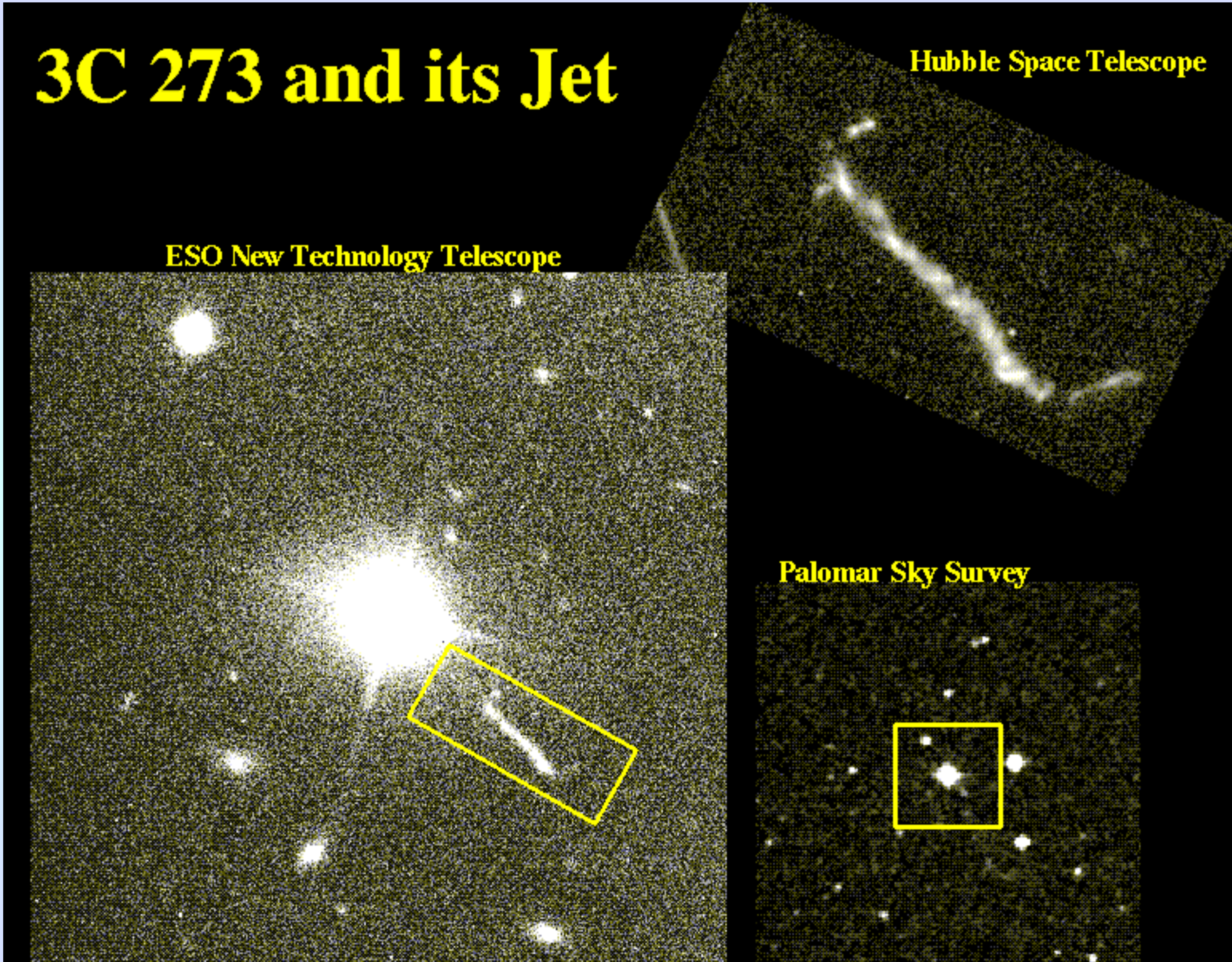
Quasars

Quasars are the brightest (isotropically radiating) objects in the universe; their luminosity overwhelms whatever galactic light is surrounding it.



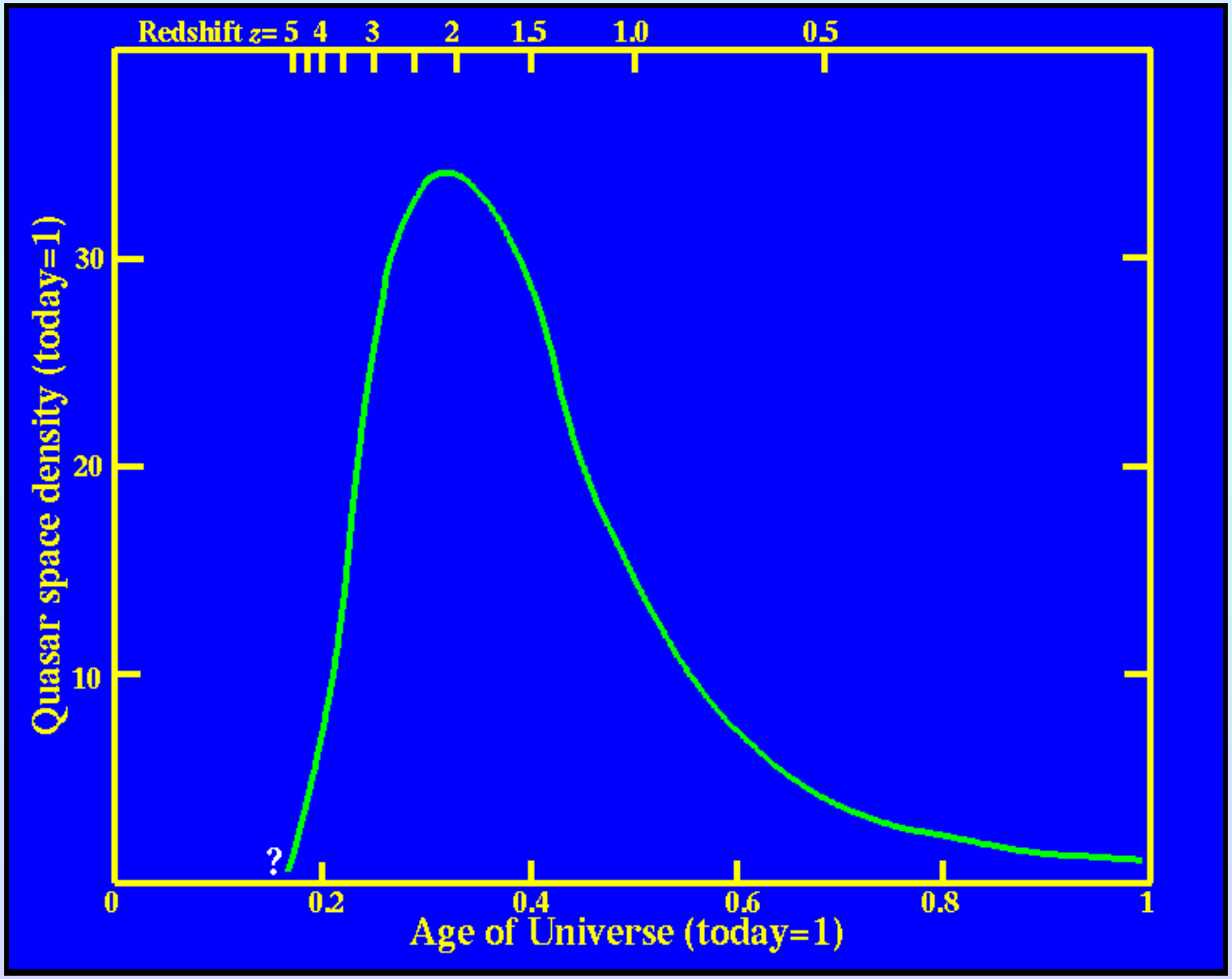


3C 273 and its Jet



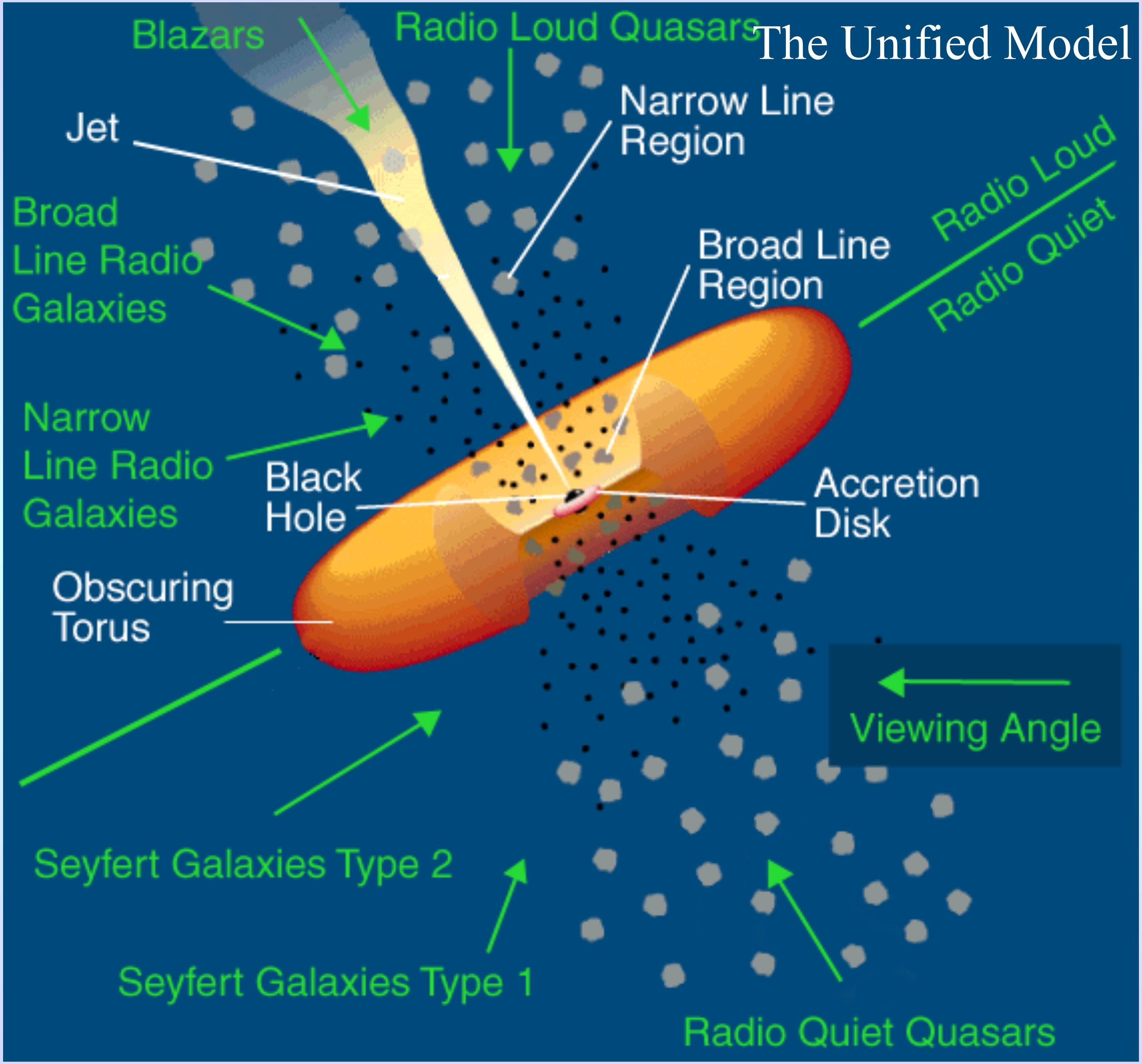
Quasars

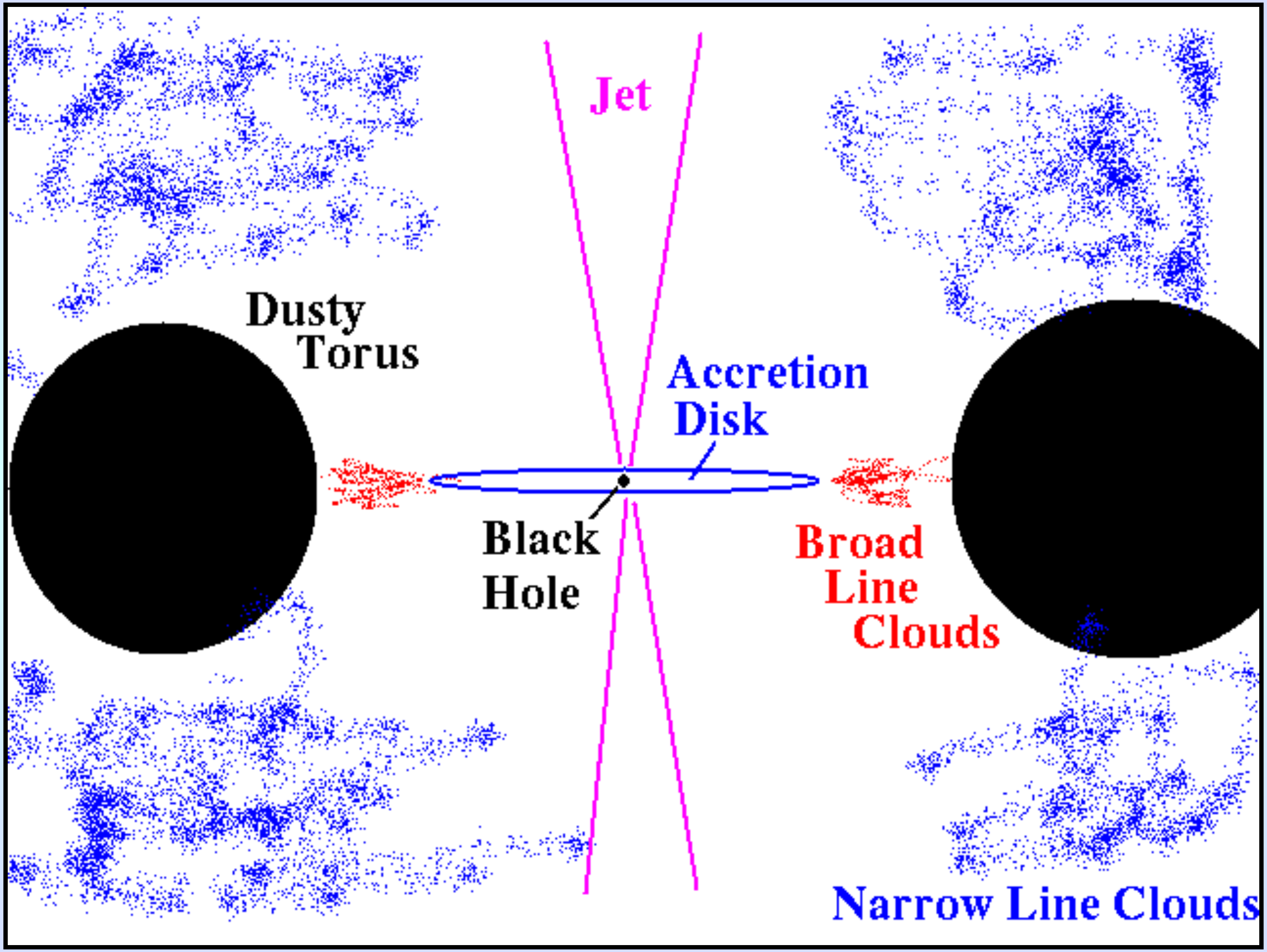
Quasars have evolved significantly over the history of the universe. The “age of quasars” was 10 billions years ago, when the universe was ~1/4 of its present size.



AGN Unified model

- AGN are all powered by an accretion disk around a supermassive black hole (with masses up to ~ $10^8\ M_{\odot}$).
- Gas clouds surround this central engine, with the clouds of the broad-line region (BLR) close in (~ 0.1 pc) and the narrow-line regions (NLR) further out.
- A dust torus surrounds the central engine and the BLR and is aligned with the accretion disk. The orientation of the dust torus relative to the line of sight affects the appearance of the AGN.


The Unified Model
Blazars
Radio Loud Quasars
Jet
Narrow Line Region
Broad Line Radio Galaxies
Radio Loud
Radio Quiet
Broad Line Region
Narrow Line Radio Galaxies
Black Hole
Accretion Disk
Obscuring Torus
Viewing Angle
Seyfert Galaxies Type 2
Seyfert Galaxies Type 1
Radio Quiet Quasars


Jet
Dusty Torus
Accretion Disk
Black Hole
Broad Line Clouds
Narrow Line Clouds

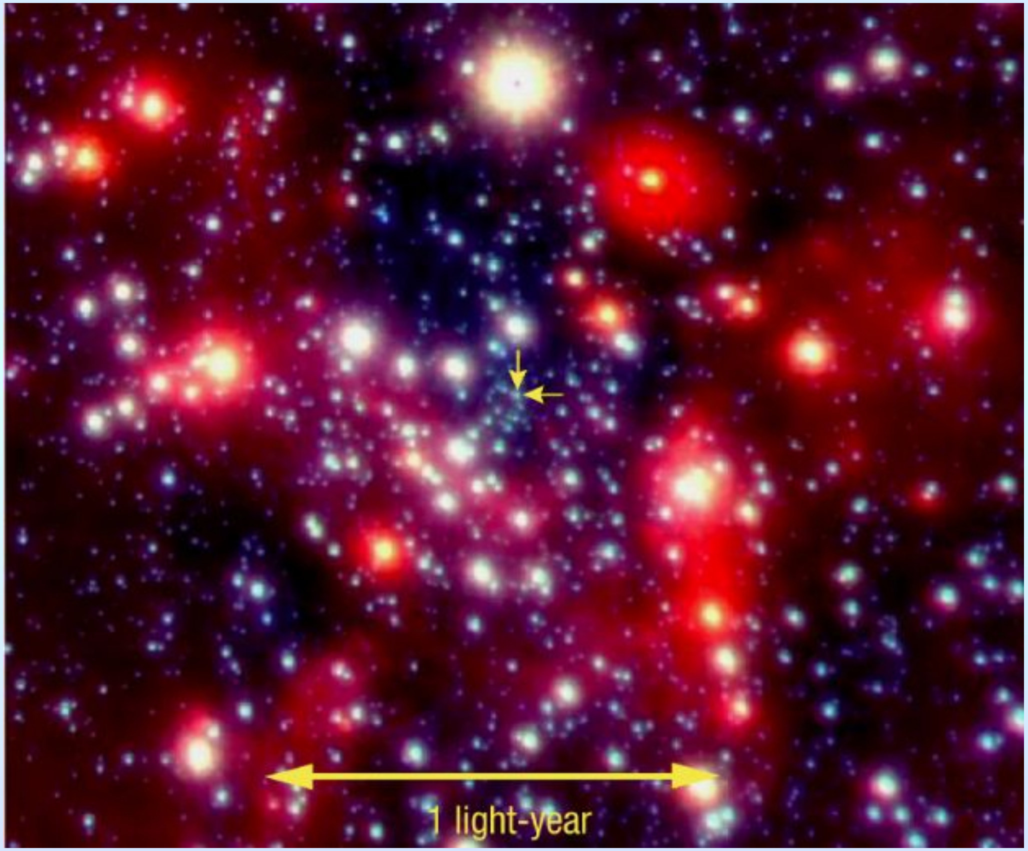
AGN Unified model

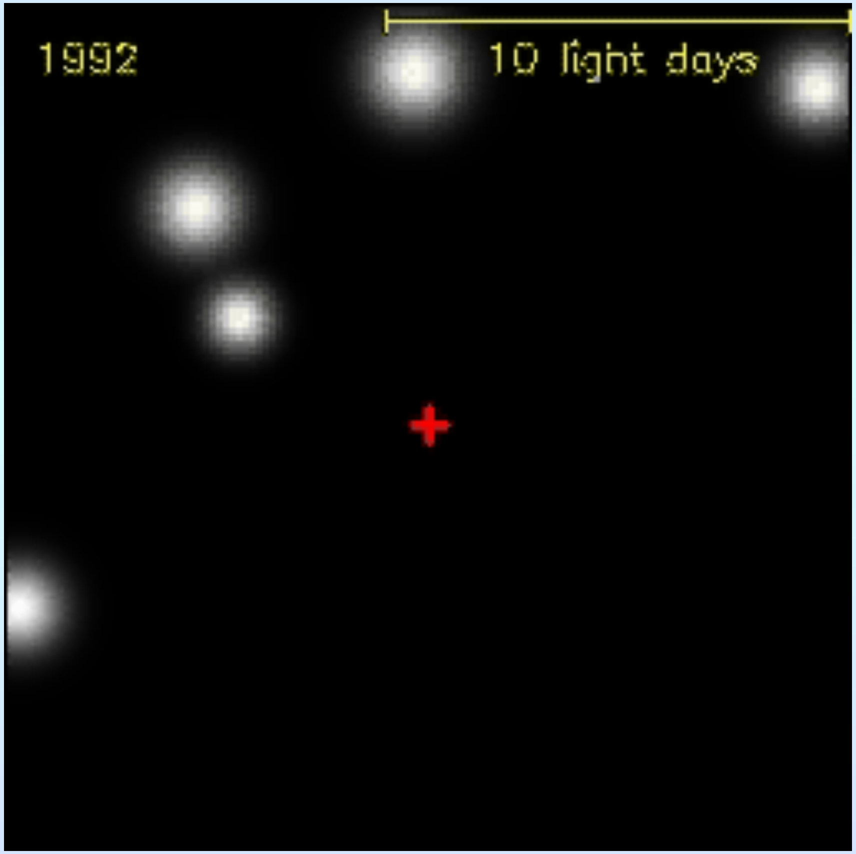
- Different wavelength light comes from different areas
  - X-ray + UV from innermost parts of disk and jet
  - Radio from particles accelerated to relativistic energies in the jet (synchrotron radiation)
  - Visible light (continuum) from farther out in disk or jet
  - Visible light (emission lines) from BLR and NLR clouds
  - Infrared from radiation from surrounding dust grains, either in clouds or in the torus
- The existence of so many high-redshift AGN, coupled with a reasonable duty cycle, implies that many/most/all present day galaxies contain supermassive black holes in their core. Whether or not they are active depends on whether they are accreting.

Black Hole Mass Measurements

Masses for Central Black Holes come from 4 sources:

- Proper motions and radial velocities of the Galactic Center





The Galactic center is known as Sagittarius A*. The stellar motions imply a central black hole mass of $\sim 4.0 \times 10^6\ M_\odot$.

Black Hole Mass Measurements

Masses for Central Black Holes come from 4 sources:

- Proper motions and radial velocities of the Galactic Center
- Virial analysis of stellar velocity dispersions

At ground-based resolutions, the central increase in velocity dispersion can be blurred out. High spatial resolution is needed.

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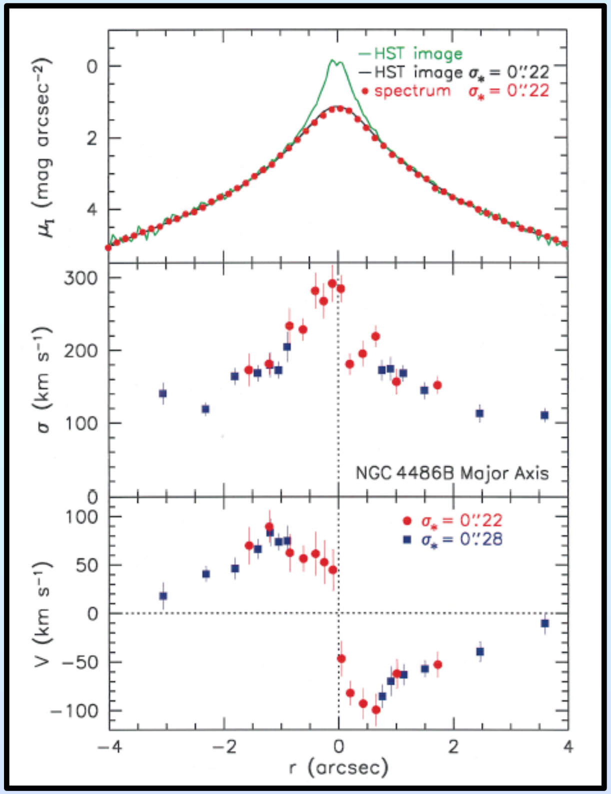

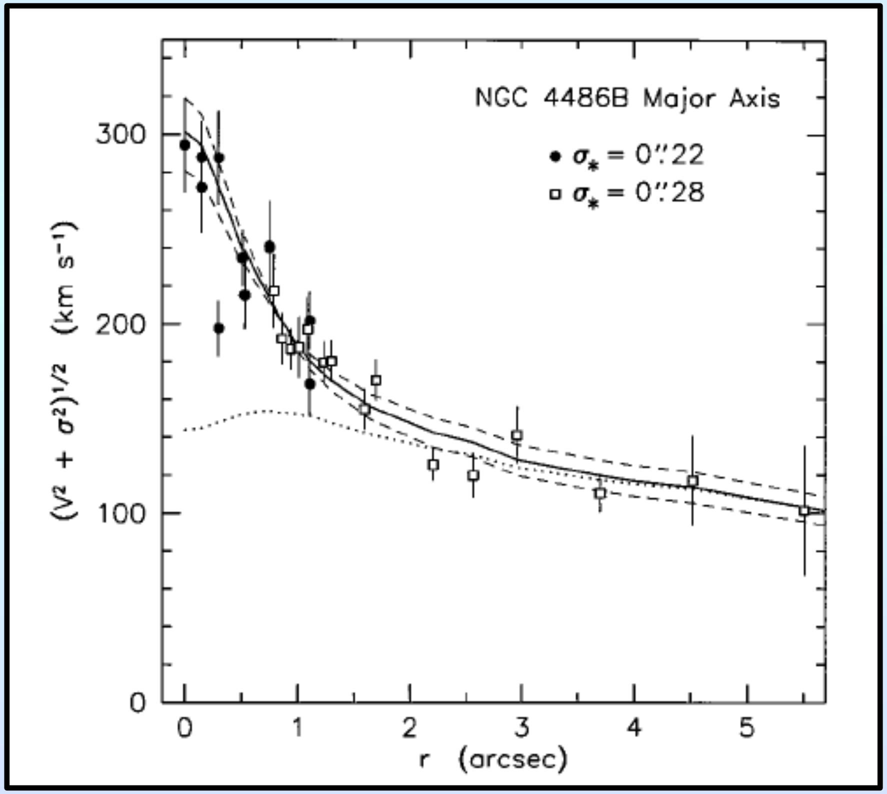

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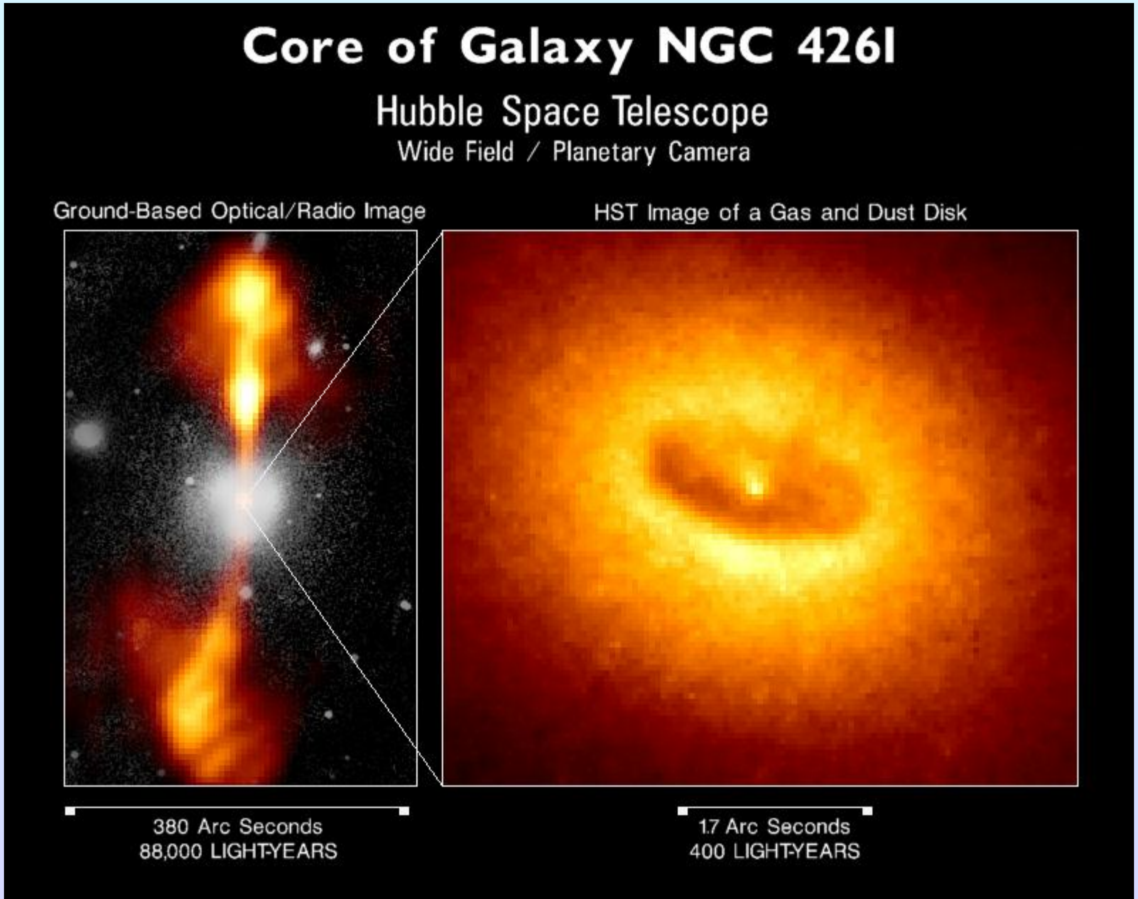
Black Hole Mass Measurements

Masses for Central Black Holes come from 4 sources:

- Proper motions and radial velocities of the Galactic Center
- Virial analysis of stellar velocity dispersions
- Rotation velocities of central gas disks

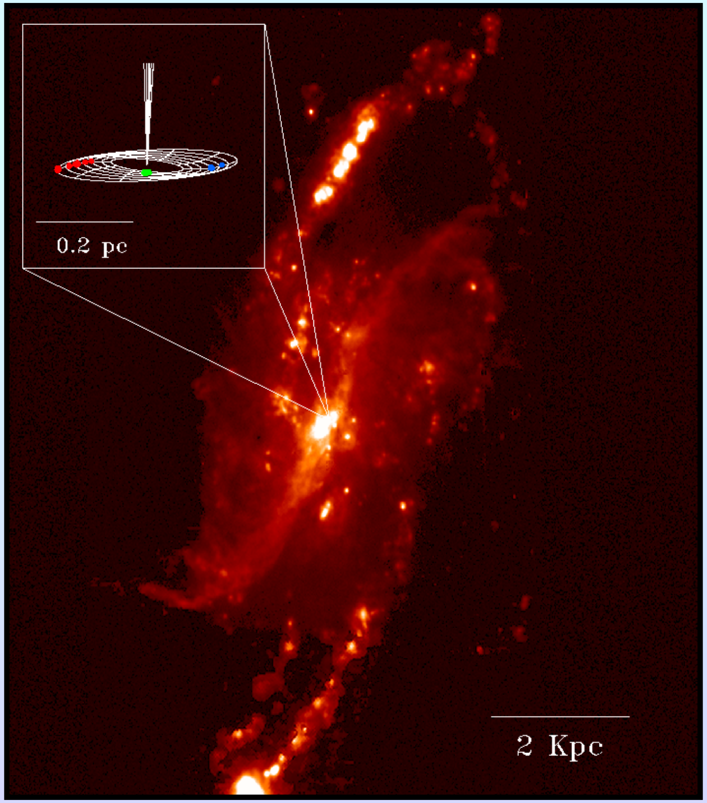
HST images reveal that some galaxies (even ellipticals) have gaseous, dusty disks in their core.

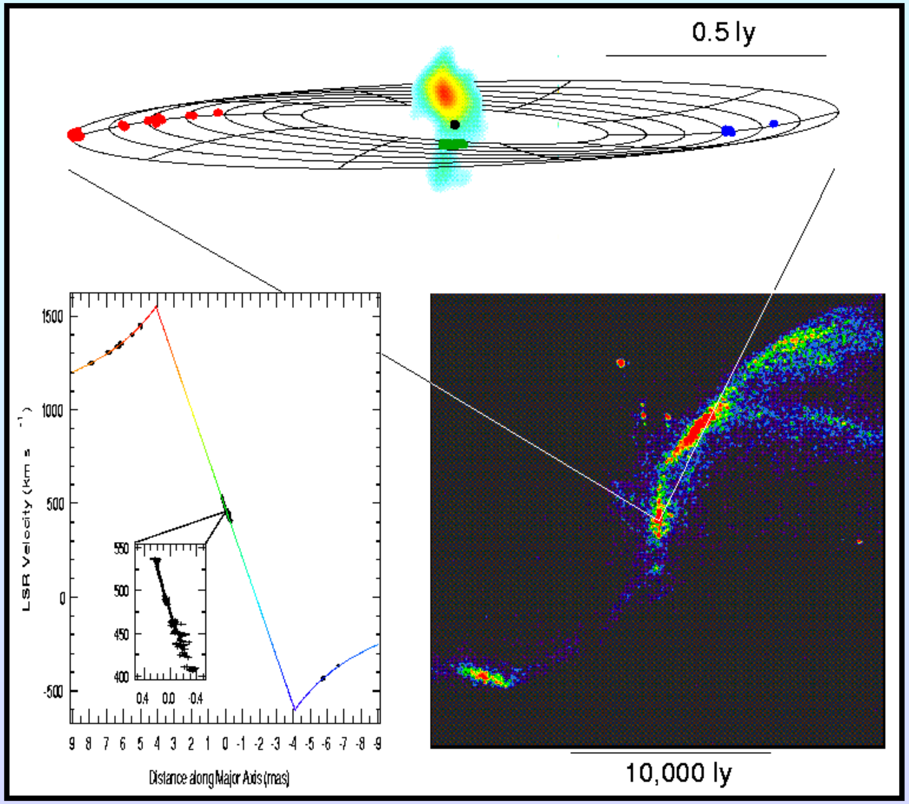


Black Hole Mass Measurements

Masses for Central Black Holes come from 4 sources:

- Proper motions and radial velocities of the Galactic Center
- Virial analysis of stellar velocity dispersions
- Rotation velocities of central gas disks
- Megamasers





Black Hole – σ Relation

There is an apparent correlation between the mass of a galaxy's central black hole mass and the velocity dispersion (i.e., mass) of its *spheroidal* component. [Note: some recent mega-maser mass estimates appear to lie below this relation.]

The black hole appears to know about the rest of the galaxy.